THE USE OF A PNEUMATIC BREAKWATER IN AMPHIBIOUS WARFARE

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THE USE OF A PNEUMATIC BREAKWATER IN AMPHIBIOUS WARFARE

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Engineering from
Princeton University, 1957

PREFACE

The military operations used as examples in this thesis are from World War II. I realize that military men are frequently criticized for "fighting the last war" when planning and training for future ones. However, in spite of the advances in airborne operations, both by parachute and by vertical takeoff planes of all types, it is my conviction that most of the supplies used in support of an amphibious operation, at least in the foreseeable future, must be landed by water. Additionally, alternate plans must be prepared for amphibious operations in case of bad weather curtailing or cancelling flight operations.

C. M. H.

Acknowledgments

The author wishes to acknowledge to VADM W. Mack Angas, CEC, USN (ret.), Chairman of the Department of Civil Engineering, Princeton University, his appreciation for the help so willingly offered and to the faculty of the Department of Civil Engineering for their guidance in many fields throughout the year's work at Princeton.

Appreciation to: Mr. Philip Brasher, Dr. John H. Carr, Mr. A. H. Laurie, Professor M. Kurihara of the Japanese Research Committee for Hydrology, and the U. S. Navy Hydrographic Office for their assistance and suggestions; Major R. R. Minor, USMC, for his help in preparing Chapter I; Mr. Hajima Toshiki for his translation of <u>On the Study of a Pneumatic Breakwater III</u>; my wife Joan, for her assistance in proofreading the manuscript, and Mrs. Jeanne Silvester for typing the stencils; is gratefully acknowledged.

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List of Symbols Used

a	Horizontal amplitude of a particle in orbit
a_1	Parameter $= 4\alpha\beta k_1 h$
b	Vertical amplitude of a particle in orbit
C	Wave velocity
C_c	Velocity of Tidal current
C_g	Velocity of a wave group; velocity of wave energy
C_o	Deep water wave velocity
C_r	Velocity of a wave relative to a current
C_2	Velocity of a wave relative to the ground
d	Depth of water
E_t	Total wave energy in one wave length
g	Acceleration due to gravity
H	Wave height
H_b	Breaking height of wave
H_o	Deep water height of wave
h	Depth of horizontal current
h_o	Atmospheric pressure
k	$k = 2\pi/L$
k_1	Wave number
k_i	Imaginary part of k
k_o	Initial k of a wave before it is modified by a breakwater
L	Wave length
L_o	Deep water wave length
M	$M \approx \dfrac{\pi^2}{2\tanh^2\left(\dfrac{2\pi d}{L}\right)}$

P	Power
Q	Volume of air
T	Wave period
t	Time
U	Velocity of horizontal water current
W	Velocity of vertical water current
x	Horizontal distance from the air pipe
Y	Parameter $= kU/\sigma$
Z	Parameter $= hg/U^2$
z	Depth
α	Coefficient for U denoting turbulent velocity
α_1	Parameter $= g/U\sigma$
α_m	Limiting value of α_1
β	Coefficient for h denoting mixing distance of turbulence
δ	Ratio of $4U/C$
ξ	Parameter $= Q/g^{1/2}z^{3/2}$
ρ	Density of water
σ	Frequency of a wave

CHAPTER I

THE EFFECTS OF WAVE ACTION ON AMPHIBIOUS OPERATIONS

Amphibious warfare was studied by the U. S. Marine Corps and Navy during the 1920's and 1930's. The free world is very fortunate that this phase of warfare was so well developed during this period, as World War II became very much of an island-hopping campaign in the Pacific, and amphibious operations played a major part in the outcome in the Atlantic.

An amphibious landing consists of several phases. The first combat operation is the pre-landing bombardment by naval warships and the bombing by land-based and carrier-based planes, which take place for days or even weeks before D-Day. The purpose of this bombardment is to destroy, to the maximum extent possible, the defenses which the enemy has erected and to minimize his ability to fight back when invaded. This phase is extremely important and can reduce the casualties among the landing troops considerably. On D-Day the transports, landing ships and craft, and the auxiliaries arrive in the objective area. The troops are loaded into amphibious vehicles (LVT's, LVT(A)'s and DUKW's) and landing craft (LCVP's, LCVP's and LCM's). As H-hour approaches the amphibious vehicles and landing craft form into waves and proceed into the beach on a regular schedule. The amphibious vehicles go first as they provide more protection for the troops and can be

driven onto the beach. Throughout this day and the succeeding ones additional troops and supplies are brought ashore in support of the assault waves. During WWII glider and parachute troops were also landed in some amphibious operations. Present day Marine Corps plans call for the use of helicopter-borne troops to seize dominating terrain in order to supplement the surface ship to shore movement. In addition the Army is planning to use parachute troops. During the landings and in the ensuing battle, naval guns and air support are used to destroy enemy emplacements and strong points. Inasmuch as the 16" guns on battleships can fire precisely at ranges of more than 15 miles, and smaller guns at shorter ranges, they are of great assistance to the landing force. Aircraft are especially valuable when the troops have advanced beyond the range of the naval guns.

In contrast to Napoleon's army which "Marched on its stomach", the logistics problem of modern warfare is staggering. In the 28 days following the invasion of Normandy 1,000,000 men, 183,000 vehicles and 650,000 tons of supplies were unloaded over the beaches and through the artificial ports, by a force of 2,000 - 3,000 craft and 15,000 men. (1)

> "The most significant logistical characteristic of an amphibious operation is the requirement for the establishment of a system of logistical support which ensures that the necessary support for a landing force

(1) Dr. Alfred Vagt, Landing Operations, Military Service Publishing Company, Harrisburg, Pa., 1952, p. 41, quoted UP dispatch from Allied Naval HQ, London, 8 August, 1944.

is provided throughout the landing and assault phases of the operation, without a loss in momentum, until routine procedures of land warfare can be instituted ashore."

The assault waves of troops carry only rations, water, and a limited amount of ammunition ashore with them. Their emergency resupply consists of floating dumps. These dumps are landing craft or amphibious vehicles, loaded with supplies which will be required in the early hours of the battle. The floating dumps are called into the beaches upon request of a tactical commander in need of more supplies. As the battle progresses and the beachhead is enlarged, larger quantities of supplies are brought in to reinforce the limited amounts on hand.

The success of a landing depends upon sufficient logistical support so that ammunition, food, water, gasoline, etc., are not wanting at any point. The most critical phase of the landing is in the early stages when supplies are low and the defenders are attempting to push the invaders back into the sea. During this phase a constant flow of supplies must be transported by landing craft or amphibious vehicles to the beach. Anything interfering with these craft jeopardizes the success of the operation.

Heavy seas are one of the great dangers during this type of operation as they make resupply very difficult. They affect operations by making it difficult to lower boats alongside the ships, by making it risky and time consuming to lift supplies and equipment out of the holds of ships, and by increasing the possibility of landing craft capsizing and sinking or broaching on the beach.

1) U.S. Marine Corps, Logistical Support (Including Personnel) Landing Force Manual 20, Washington, 1952, p. 2-1.

The height of waves has a direct effect on the amount of tonnage that can be unloaded over the beach. Figure 1 shows the relationship between tonnage unloaded and wave heights for the first two weeks of October, 1944 at Omaha Beach, Normandy.

The landings at Bouganville in the Solomon Islands were hampered by the heavy surf conditions at the time. The surf made some of the beaches unusable thus increasing the load on the others. (1)

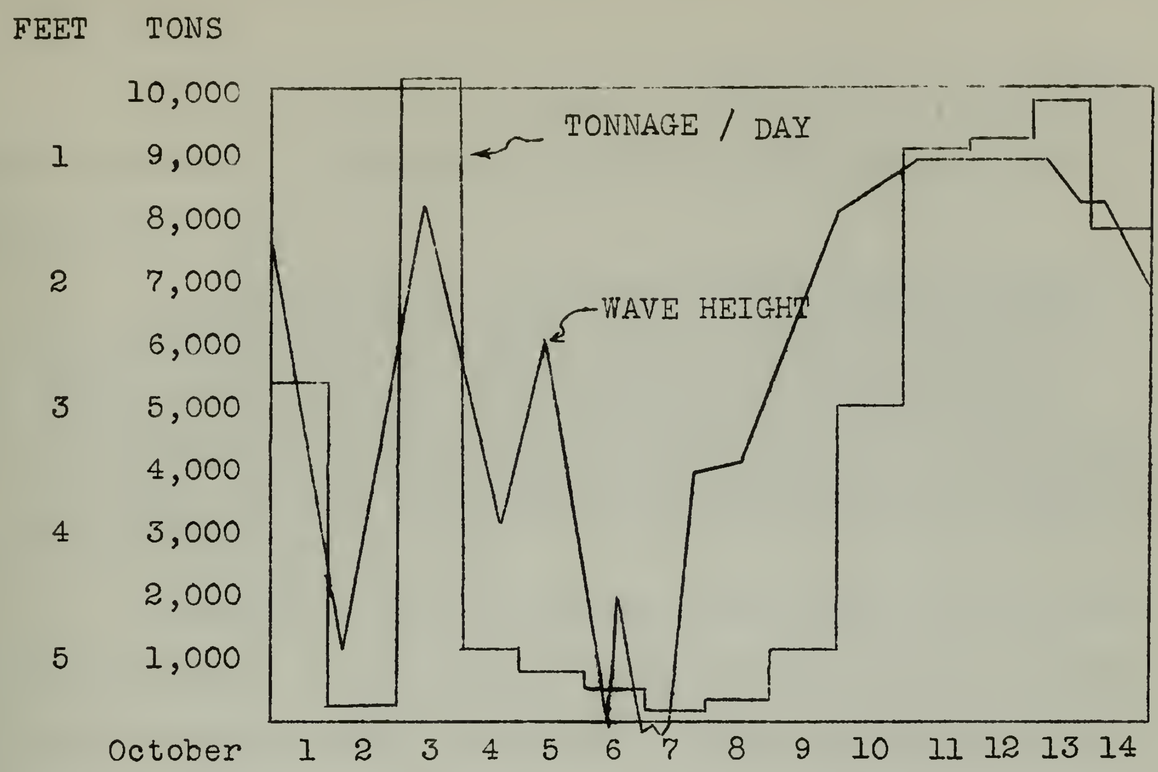
Surf conditions also played a large role in the battle for Iwo Jima. The weather was moderate during the landings on the morning of D-Day.

> "The weather deteriorated toward mid-afternoon on the first day, and thereafter was most erratic. (2) It was necessary to open up the alternate beaches and to shuttle back and forth in search of a lee coast. The offshore gradient was steep, especially along the preferred beaches, and waves sometimes towering ten feet broke directly on the narrow shelf below the first terrace. The downward thrust of the breakers and the outward pull of the undertow were so great that some 200 of the smaller landing craft were lost, most along the beaches. If the ramp were down they were apt to fill with sand and water, and if not, they were likely to be broached by the next wave. The tractor and DUKW drivers, unless they rode the crest of a wave onto the terrace and secured a good purchase, also found their vehicles at least temporarily out of commission. (3)"

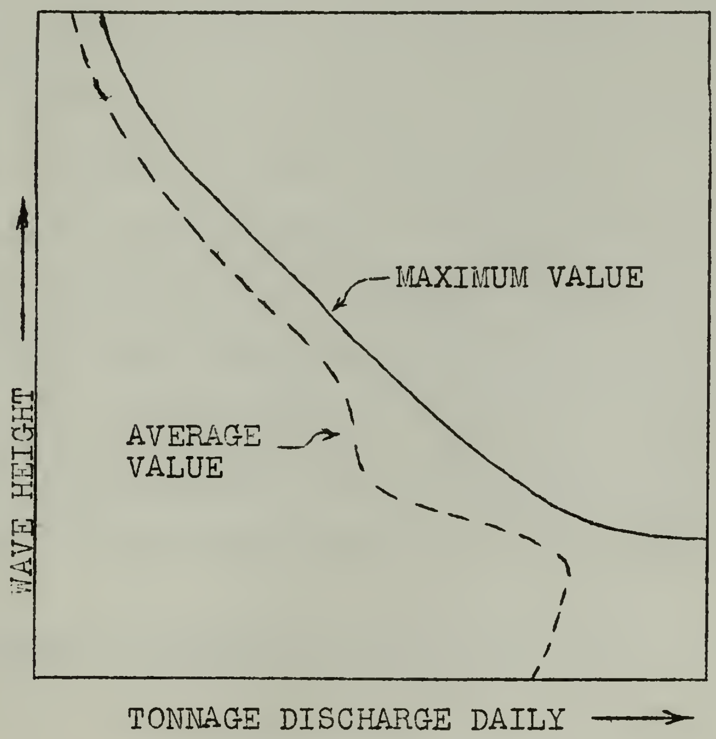
(1) Samuel Eliot Morison, Coral Sea, Midway, and Submarine Action Little, Brown and Company, Boston, 1949, p. 303.

(2) Jeter A. Isely and Philip A. Crowl, The U.S. Marines and Amphibious War, Princeton University Press, Princeton, 1951 p. 517, from Commanding General, 5th Marine Division, Iwo Jima report, Records Section, Marine Corps School.

(3) Ibid p. 517, from Commanding General, 5th Amphibious Corps, Appendix 10 to Annex C to Iwo Jima report, Records Section, Marine Corps Schools.



Effect of wave height upon amount of tonnage unloaded daily at Omaha Beach, Normandy during the first two weeks of October, 1944.



...re 1. Relation between rate of unloading and the wave height at Omaha Beach, Normandy. From C.C. Bates, "Wave Forecasting in Invasions", Annals New York Academy of Sciences, Vol 51, p. 559.

Iwo Jima points out well the differences between an ideal beach for an amphibious operation and the one that is available for use.

> "A beach with no obstructions or defenses seaward or landward; with deep water close to shore; with a firm but not rock bottom; with no tides, currents or surf; with a gradient which will permit the beaching and retraction of all types of landing craft and ships under all conditions of load at any desired time, and not excessive for the use of vehicles; with excellent trafficability and with adequate exits for personnel and vehicles would be an ideal beach". (1)

Strategic conditions dictate what lands or islands have to be taken. Within these dictates there may be a choice of several landing areas; However, as nature seldom provides all of the attributes of an ideal beach in any one location, it is necessary to improvise and to approach these conditions as closely as possible. To combat poor beach soil conditions large quantities of steel matting were used during WWII so that the beach would be trafficable for vehicles. A great deal of research is being conducted to solve this problem.

The problem of controlling the surf at a landing site was tackled only once, at Normandy, during WWII and not at all during the Korean War. (The installations at Normandy are discussed in Chapter III of this paper.) Despite the steps taken in the use of mobile breakwaters at Normandy, much remains to be done in this field so that unfavorable surf conditions will be

(1) U. S. Marine Corps, Logistical Support, p. 3-2.

ameliorated in every landing. The requirements for a mobile breakwater in amphibious warfare are:

1. The breakwater must be effective in stopping waves. A calculated risk may be assumed and only waves of a limiting height and length considered. At Normandy the design wave was 8 feet high and 120 feet long.

2. The breakwater should be easily and economically (in time, facilities, and personnel) made and easily transported to the operating area.

3. The protection must be capable of being quickly placed with a minimum of demands for assistance from tugs and other ships and a minimum of interference with the landing operations proper.

4. The breakwater must be durable enough to last for the anticipated duration of the amphibious operation.

5. The breakwater must be firmly maintained in place.

CHAPTER II

WIND, WAVES AND SURF

In order that we can determine the requirements for wave and surf protection, we must review the nature and characteristics of gravity ocean waves.

The mass of water in a wave does not move shoreward with the velocity of the wave but oscillates back and forth. This will be confirmed by anyone who has watched driftwood bobbing up and down with the passing of each wave and moving only slightly in the direction of the wave progression. Waves are composed of particles of water that move in orbits, the particles in the same vertical plane parallel to the wave crest moving in phase together. As the particles reach the top of their orbit the crest of the wave passes them; as they reach the bottom of their orbit the trough goes by. The Stokian, or irrotational, theory, which has been observed to be closer to the actual conditions than other proposed theories, states that the orbits are not closed, but that a particle advances slightly in the direction of the wave motion each time it goes around its orbit. This advance of water is known as mass transfer. The velocity of the mass transfer is shown in table 1.

Period (seconds)	Length (feet)	4	6	8	10	12	20	30
4	82	0.3	0.7	1.3	1.9			
6	184	.1	.2	.4	.6	.8	2.0	
8	328	.04	.08	.15	.2	.4	.9	2.0
10	512	<.04	.04	.08	.1	.2	.5	1.0
12	738	<.04	<.04	.05	.07	.1	.3	.6
14	1003	<.04	<.04	<.04	.04	.07	.17	.4

Table 1. The velocity of mass transfer.

Henry B. Bigelow and W. T. Edmundson, <u>Wind Waves at Sea, Breakers and Surf</u>, Hydrographic Office, U. S. Navy Publication H.O. #602, Washington 1947, p.6.

The physical characteristics of a wave are shown in the cross section of a wave in Figure 2.

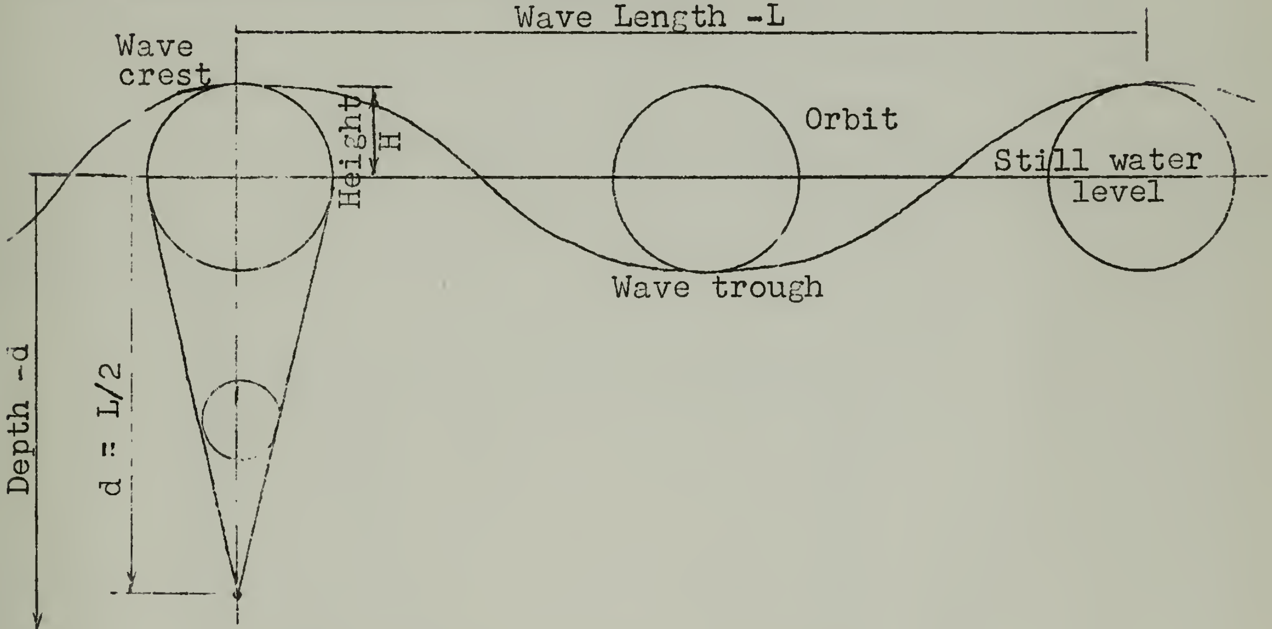


Figure 2. Wave characteristics in deep water.

The approximate amplitude of movement of a particle can be expressed by the following formulas:

$$a = H \frac{\cosh \frac{2\pi(d+z)}{L}}{\sinh \frac{2\pi d}{L}}$$

$$b = H \frac{\sinh \frac{2\pi(d+z)}{L}}{\cosh \frac{2\pi d}{L}}$$

"a" horizontal amplitude of the orbit
depth of particle, downward measured negatively
"d" depth of water
"L" wave length
"H" wave height
"b" vertical amplitude of the orbit

As $\frac{d}{L} \rightarrow \infty$ i.e. in a deep water wave $a = b = He^{\frac{2\pi z}{L}}$, and therefore, the particles are moving in circles whose diameters decrease rapidly with increasing depth. (See figure 3). At a depth of z=L/2, "a" and "b" are only 4% of their surface values, and therefore, there is little energy in the wave beneath this depth. (Deep water waves are defined as those waves whose $\frac{L}{d}$ is less than 2.) Hence, when constructing a breakwater in deep water, it is necessary to have the breakwater extend only to a depth equal to one-half of the design wave length. This principle is one of the bases of the design for the floating breakwaters used at Normandy and discussed in Chapter III.

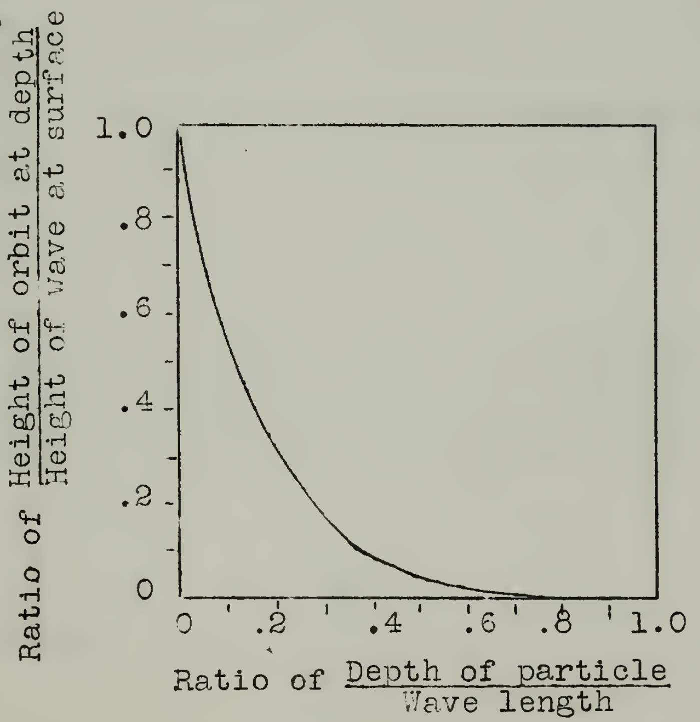


Figure 3. The relationship between the amplitude of an orbit and the relative depth of the orbit.

It must be noted that this circular orbit is true only when $d/L \longrightarrow \infty$. For all other cases the value of "b" decreases more rapidly than the value of "a", and hence, the circular orbit, at the surface, changes to an elliptical motion as the depth increases, until, at the bottom, the theoretical motion is a backward and forward one.

In shallow water, as $d/L \longrightarrow 0$, the amplitude of a particle becomes:

$$a = H\,(L/2\pi d)$$
$$b = H\,(1+z/d)$$

The orbit in shallow water is elliptical. The horizontal (major) axis remains nearly constant while the vertical (minor) axis decreases directly with depth. Shallow water waves are defined as those in water of less depth than L/25.

The generation of waves in deep water is independent of depth and is a factor of three things, the strength of the wind, the duration of the wind and the length of the fetch. These parameters have been plotted by C. L. Bretschneider. (1) The wave height and period can be determined from the graph knowing the three parameters. With these characteristics of the wave the other physical features can be determined.

(1) Beach Erosion Board, Corps of Engineers, Technical Report #4, Washington, 1954, p.16, from C. L. Bretschneider, "Revised Wave Forecasting Relationship", Proceedings of Second Conference on Coastal Engineering, 1952.

$C^2 = \frac{gl}{2\pi} \tanh \frac{2\pi d}{L}$, where C is the wave velocity. This is an approximation of Stokes equation for C. In deep water $\tanh \frac{2\pi d}{L} \rightarrow 1$ and $C^2 = \frac{gL}{2\pi} = 5.12L$. $L = CT$, T is the wave period; therefore, $L = 5.12\ T^2$.

To illustrate the determination of wave characteristics, a wind of 30 knots is assumed to blow over a fetch of 200 nautical miles for a period of 12 hours. From Bretschneider, it is seen that this wind will produce a wave 15 feet high with a period of 9 seconds. The length of the wave would be $5.12 \times 9^2 = 414$ feet, and its velocity would be $C = L/T = 414/9 = 46$ '/sec or 27.3 knots. Although the wave crest travels at this high speed, the particles of water at the surface move only at a speed of $\frac{\pi H}{T} = \frac{3.14 \times 15}{9} = 5.21$ '/sec. or 3.1 knots; therefore, it is seen that, despite the high velocity of the wave crest, the horizontal velocity of the water is quite low at the crest and trough of the wave and decreases to 0 during intermediate phases of its orbit. As a consequence, the horizontal motion of the orbits in the open sea has only a slight effect on ships and boats.

> The question of the orbital velocities at the top of the crest at the instant of breaking has not received as much attention as it deserves from a practical standpoint. But anyone who has had experience in surf knows that any object such as a plank or a small boat floating on the top of a roller, may be swept forward with astonishing rapidity just as the top of the crest falls forward if the breakers are of the plunging type. And this is one of the reasons why it is so difficult to bring even a surfboat in through high breakers, for it is likely to be carried forward over the crest unless it is well handled, to be pitched down

bow foremost into the trough ahead, where it will be in imminent danger of broaching to, as its stern continues to be swept forward in the air, or at the least of filling with the water that pours down upon it from above. Surf running of this sort should never be attempted in small boats, except as a last resort. (1)

Waves in a group are not all of the same height, as puffs of wind during the wave generation produce waves of unequal size. The height of waves used in waterfront design work is the "significant height". This is the average height of the highest 1/3 of the waves.

As the waves pass out of the generating area they lose their choppy characteristics and become swells, the crest taking on a more rounded appearance. As the wave group proceeds, the wave in the front of the group dies out while another wave is generated at the rear of the group; therefore, the group velocity Cg, is lower than the wave velocity, C.

$$C_g = nC \text{ where } n = 1/2\left[1 + \frac{\frac{4\pi d}{L}}{\sinh \frac{4\pi d}{L}}\right]$$

In deep water n = 1/2, and the group velocity is 1/2 the individual wave velocity. In shallow water n = 1, and the group velocity is the same as the wave velocity.

During the time the waves are moving from the generating area to a shore, they are decaying. The length of the waves increases and the height decreases, until at a great distance from the fetch, the wave has a negligible height and ceases to be important. The period and height of a swell during this travel can be

(1) Henry B. Bigelow and W. T. Edmondson, Wind, Waves at Sea, Breakers and Surf, Hydrographic Office Publication No. 602, Washington, 1927, p. 110.

found on graphs, prepared by Bretschneider (1), knowing the period and height of the wave at the end of the fetch, the minimum fetch distance for the wave, and the decay distance. Aerologists can forecast the wave condition at any location if they have the weather reports over the ocean for the preceding days.

As the waves approach shallow water they become influenced by the bottom. The velocity of the waves is reduced and the length decreases while the height first decreases mildly and then increases rapidly. (See Figure 4.) The velocity of a wave in shallow water is a function of the depth, $C^2 = gd$; therefore waves of all lengths travel at approximately the same speed as they approach the breaker line.

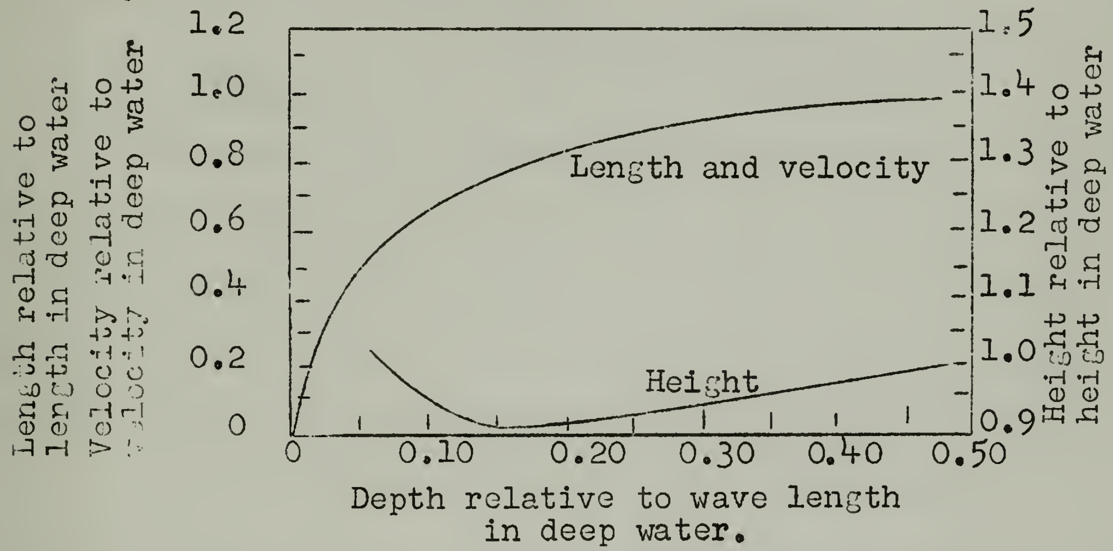


Figure 4. The change in wave characteristics with shoaling water.

Henry B. Bigelow and W. T. Edmondson
Wind, Waves at Sea, Breakers and Surf,
p. 103.

(1) Beach Erosion Board, p. 19.

When the steepness (H/L) becomes approximately 1/7, the shape of the wave theoretically is no longer stable, and the wave breaks. Actually, the wave frequently breaks before this steepness is reached due to the change in the wave profile that flattens and lengthens the trough while shortening and peaking the crest (1).

Another factor governing the breaking of waves is the relative depth of the water and the wave height. When the water shoals to a depth equal to 1.3 H the waves will break. The 1.3 factor varies with the current, wind, and local conditions but is a close approximation. The height of breaking can be expressed also as a function of the deep water wave height and length.

$$\frac{H_b}{H_o} = \frac{1}{3.3(H_o/L_o)^{1/3}}$$

where the subscript b indicates condition at breaking and the o conditions in deep water.

When the waves approach a shore at an oblique angle to the contour lines, they are refracted. The inner end of the wave crest feels the bottom first, at d = L/2, and slows down. This successive slowing down of the wave along its crest turns the wave crest in toward the beach and expands the wave along its crest.

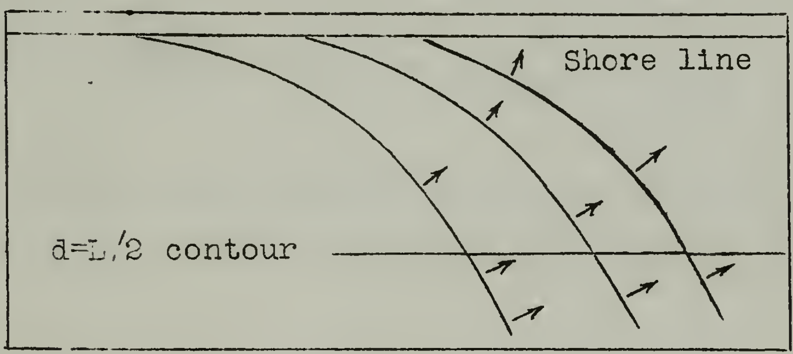


Figure 5. Refraction of a wave.

(1) Henry B. Bigelow and W. T. Edmondson, Wind, Waves at Sea, Breakers and Surf, p. 131.

he wave energy between any two orthogonals remains constant during refraction. As the wave is refracted and the crest expanded, the energy is distributed over a longer wave crest, hence the energy per foot of wave crest is reduced and the height of the wave is lowered. (See table 2).

Percentage decrease in height between deep water and the breaker zone, for waves of different initial degrees of steepness approaching a straight shore line (with straight and parallel bottom contours) at different angles. It is assumed that the waves break where the depth of water is 1.3 times the breaker heights.

Steepness of wave in deep water (length:height)	Angle between wave in deep water and shore lin 20° Percent	30° Percent	40° Percent	50° Percent	60° Percent	70° Percent
10:1	0	3	6	11	18	30
20:1	0	5	10	16	26	38
40:1	1	6	11	17	27	39
100:1	2	6	12	19	28	40

Table 2. The reduction of wave height due to refraction.
Henry B. Bigelow and W. T. Edmondson,
<u>Wind, Waves at Sea, Breakers and Surf</u>
p. 159.

The energy in a wave is equally divided between the potential energy of the relative heights of the crest and the trough and the kinetic energy of the orbital motion. The total energy in one wave length is:

$$E_T = 8\ H^2L\ (1-M\frac{h^2}{L^2}) \quad \text{where } M = \frac{\pi^2}{2\tanh^2\left(\frac{2\pi d}{L}\right)}$$

In deep water the H/L term is small; hence, $E_T = 8\ H^2L$, and the energy builds up very rapidly with increasing wave heights.

The archives of the professional institutions abound in authoritative records of the damage and prodigious power effects of storm waves: boulders up to 15 tons weight have been washed over parapets of sea walls 10 to 12 feet above sea level; masses of masonry weighing 3000 tons have been bodily moved; an iron casting 18" in diameter and 1½" thick and embedded in concrete 30 feet above sea level has been sheared from its base; a mass of concrete weighing 70,000 tons has been washed whole from its foundations into the harbour; and so on. (1)

A breakwater sufficient to resist the onslaught of waves of this magnitude would be impossible to construct for an amphibious landing; therefore, a calculated risk must be assumed that only waves of certain limiting dimensions will be encountered during the period of operations and the breakwater designed for these waves. It is not necessary that the waves be completely eliminated behind the breakwater. If the wave height can be reduced by 50% the energy reduction would be 75%. This would greatly aid the landing operation.

The energy in a wave will be dissipated upon reaching a beach in different ways depending upon the slope of the beach. On a shallow beach the wave shape is altered until it becomes slightly concave on both slopes, and the top of the crests spills over the front of the wave. This spilling occurs over a comparatively long period, and hence the energy is dissipated over a wide surf zone.

(1) R. R. Minikin, Winds, Waves and Maritime Structures, London, Charles Griffin and Company, Limited, 1950, p. 26.

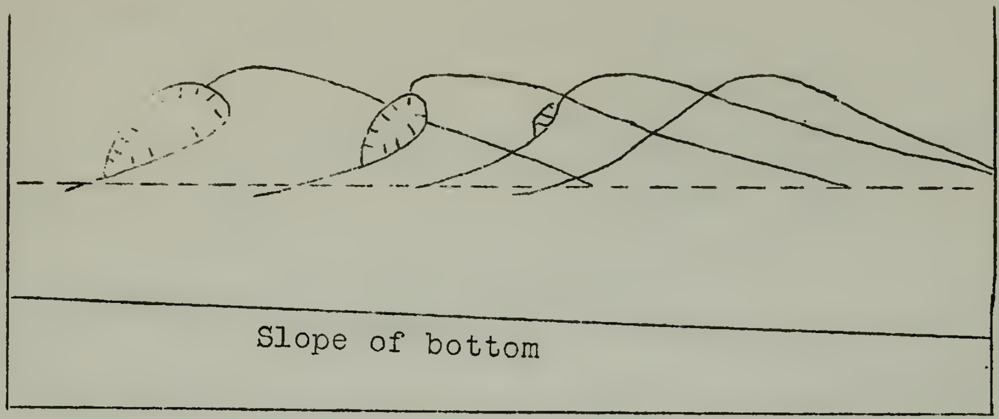


Figure 6. Profile of a spilling wave.

A plunging type of wave builds up on a beach with a moderate slope. It continues to have a convex back surface and an increasingly more concave front face until the wave breaks and plunges forward. Waves of this character are very dangerous to a craft approaching the beach and make a return to the ship from the beach a difficult job.

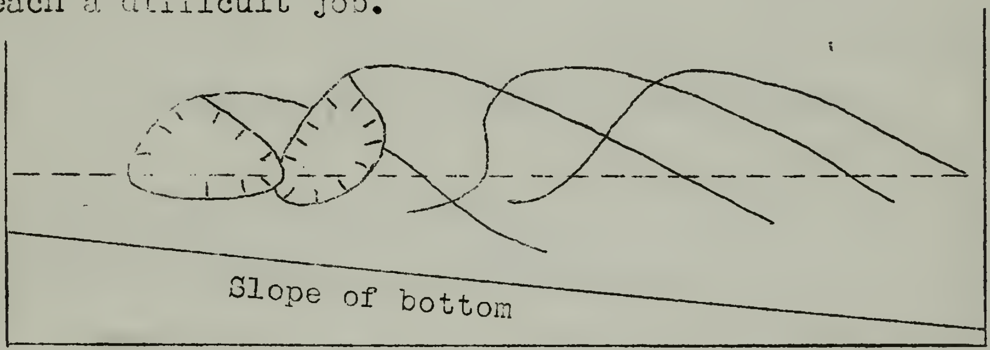


Figure 7. Profile of a plunging wave.

When a beach is steep the wave doesn't change its shape appreciably until it breaks, and then the wave surges violently up the beach. The energy in this type of wave is expended in a short distance and right on the shoreline, making

this type of breaker dangerous to beached craft.

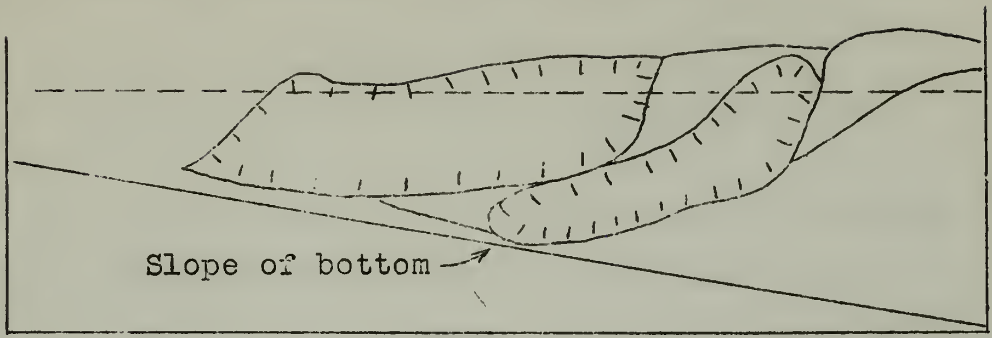


Figure 8. Profile of a surging wave.

Breakwaters are constructed to eliminate or reduce the energy from breaking waves. Gaps must be provided in the breakwater for ships to enter and leave the protected area. The waves that enter these gaps are diffracted and reduced in size. The amount of diffraction depends upon the relation between the width of the breakwater opening and the wave length. The greater the relative gap the less the diffraction. Figure 9 is a diffraction pattern for a breakwater opening equal to 2 wave lengths.

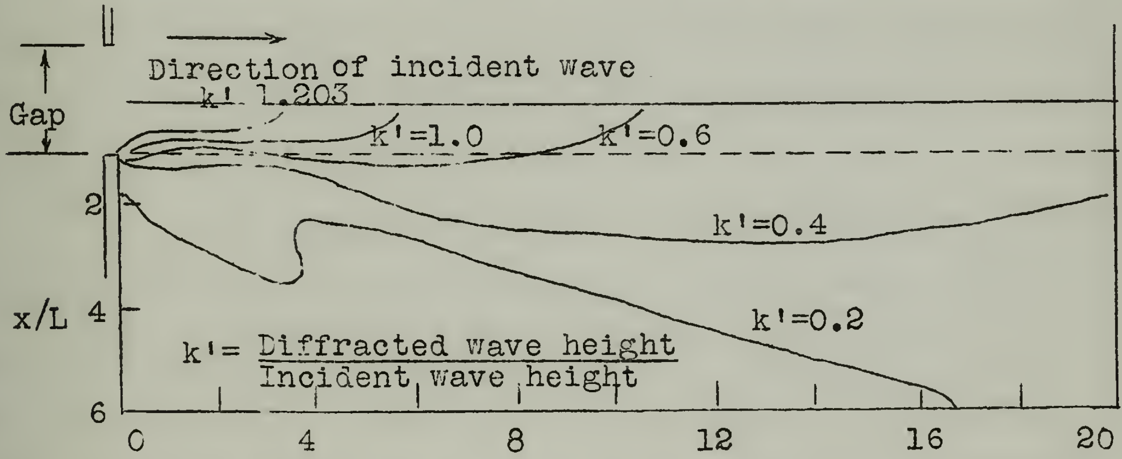


Figure 9. Diffraction of a wave entering a gap in a breakwater.

CHAPTER III

MOBILE BREAKWATERS USED AT NORMANDY

The major attempt to reduce the effects of waves during amphibious landings was made at the Allied landings at Normandy during World War II. A study of that case shows the pressing need for mobile wave protection and furnishes information on methods that have been tried to solve the protection problem.

To reconquer Europe it became necessary for the Allied forces to land in western Europe. The Axis powers knew this and heavily defended the ports of Le Havre and Cherbourg, convinced that the invading forces would have to recapture them if they were to land enough material to support the invasion. The allies realized that these ports would be extremely heavily fortified and that the casualties would be severe if the invasion took place at these ports. This was confirmed by the casualties that were suffered during the Allied raid on Dieppe; therefore, plans were made for the landings on the beaches of Normandy.

The beaches presented a difficult problem in landing supplies. The slope of the beach was approximately 1:100 and the range of tide was 22 feet. The waterline shifted back and forth for nearly 1/2 a mile during each tidal period. The beaches additionally were exposed to the waves that built up in the English Channel.

To overcome the obstacle of the flat beach a pier was designed, the inboard end of which floated as the tide came in and rested on the bottom as the tide receded. The pontoons for the pier were made of steel in the area where they would be alternately floating and resting on the bottom. The pontoons at the seaward end, that would always be afloat, were made of reinforced concrete in order to save steel. The pierheads were designed with spuds as moorings since lines to anchors would have gotten in the way of the ships using the pier. As the depth of water changed with the tide, the pierheads were jacked up or down so that they would be at the same elevation as the pier and the ship. These piers allowed heavy tanks and guns to be unloaded and moved ashore at up to 25 miles per hour. The pier was tested in the spring of 1943 and was found to be satisfactory.

The pier was designed to be used on the open beach; however, the ships could not ride alongside the piers in bad weather. Many devices were investigated to see if calm water could be provided around the pierhead.

> One of these known to us as bubbles was reported to have been successfully used many years ago, and it consisted of laying perforated pipes on the sea bed and pumping air through them. The mass of rising bubbles bursting at the surface was supposed to subdue the turbulent sea. It might have worked if we could have covered the sea bed with sufficient pipes and solved the problem of setting up the huge compressor plants which would have been required for them. (1)

(1) W. J. Hodge, "The Mulberry Invasion Harbours, Their Design, Preparation, and Installation", The Structural Engineer, Vol. 24, 1946, London, p. 129.

the plans for the invasion became firmer, the risk of bad weather on the beaches, with the inability to land the 12,000 tons of material daily to support the landing forces, became unacceptable. The decision was made to build two artificial ports, code names, "Mulberry" A and B for the American and British forces respectively. The requirements for these ports as laid down by the Chiefs of Staff were:

> Two harbours, one for British and one for American. Sheltered water to be provided by D+14, and the harbours to be large enough to develop daily discharge capacities as follows:

	American		British	
	Tons stores	Vehicles	Tons stores	Vehicles
D+ 4	1200	--	1800	--
D+ 8	3000	1250	4000	1250
D+14	5000	1250	7000	1250

> The harbours were to give sheltered water for 90 days in winds up to Force 6 (22-27 knots) at all states of the tide, to enable ships at anchor or alongside to discharge into landing craft, and to allow small craft to operate between ships and beaches
>
> They were to be large enough to give sea-room at all states of the tide-
>
> For 8 liberty ships in Mulberry B and 7 in Mulberry A to take up and leave their moorings:
>
> For about 20 coasters in Band 15 in A to proceed alongside or leave the piers or to anchor:
>
> For tugs to manoeuvre with "out of control" shipping:
>
> For about 400 mixed craft, and to give shelter during storms for about 1,000 other small craft normally working on the beaches outside the harbours. (1)

(1) Ibid, p. 144.

In fulfilling these requirements it was decided that the breakwater would have to withstand a design wave of a height of 8 feet and a length of 120 feet and would have to be durable enough to last for at least three months.

One type of protection studied was the floating breakwater. The principle of this breakwater was based on the fact that short period vibrations do not disturb a system with a long period of resonance. The idea was to construct a floating breakwater with a long natural period compared to the period of the waves that were likely to be encountered. This breakwater if firmly anchored in place would reflect the waves and provide the necessary sheltered water.

A floating breakwater, code name Lilo, made of four concentric canvas bags in the form of a sausage and ballasted was built and tested. Its main fault was that it was too vulnerable. A steel floating breakwater, "Bombardon", was then constructed. (See figure 10).

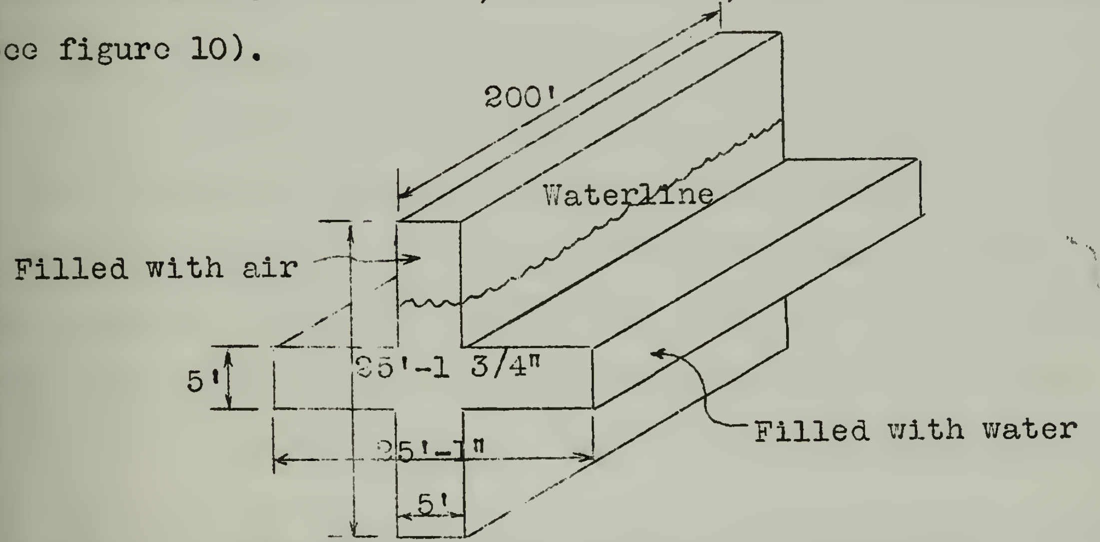


Figure 10. Unit of a Bombardon floating breakwater.

Lochner, Faber and Penney, "Bombardon Floating Breakwater", The Civil Engineer in War Vol. 2, p.

The Bombardons were to be towed in tandem and moored between fixed mooring buoys with 50 foot spacing between units. The depth of the unit was such that the orbit of the particle of the wave at the bottom of the barrier was only 30% of the height of the wave at the surface; consequently the energy passing under the breakwater was only 10% of the original wave energy. The Admiralty decided that the Bombardons should provide part of the protection required. One of the units was tested off the coast of England on April 1 and 2, 1944 and reduced a wave that was 170 feet long from a height of 8 feet to a height of 2 feet. (1)

Another method suggested was the sinking of ships to form a breakwater. This scheme had the advantage of speed, as the ships could steam into the area under their own power and then scuttle themselves in position. The ships had a height of approximately 30 feet, and with a tidal range of 22 feet they could only be used where the water was very shallow, or they would be overtopped during high tides. It was decided to use them where they could give early protection to the landing craft.

At the Quebec Conference in August 1943 it was decided to use concrete caissons, "Phoenixes", for the bulk of the protection at the harbors. Forty-three different designs for the caissons were studied. A simple design was finally selected as there was only about seven months available to complete the 147 units required to be ready by D-Day. Several sizes of the caissons were constructed

(1) Robert Lochner, Oscar Faber, and William G. Penney, "Bombardon Floating Breakwater", The Civil Engineer in War, Vol. 2, Institute of Civil Engineers, London, 1948, p. 268.

ue to the varying depths of the water in the designated location of the breakwater. The types built are listed in table 3.

Unit	Number Made	Height Ft	Length Ft in	Breadth at W.L. Ft in	Displacement. Tons	Draft Ft in
A1	80	60	204	56 3	6044	20 3
A2	11	50	204	56 3	4773	16 4
B1	31	40	203 6	44	3275	14 0
B2	24	35	203 6	44	2861	12 5
C1	17	30	203 6	32	2420	14 3
D1	10	25	174 3	27 9	1672	13 0
Ax	30	60	204	62	7700	21 5
Bx	10	40	203 6	44	3321	14 4

Table 3. The number and dimensions of Phoenix units constructed.
From: W. J. Hodge, Structural Engineer, p. 153.

Sixty-six of these caissons, including all of the Ax and Bx types, were built later to strengthen the breakwater and to prepare it for use during the winter.

In the construction of the caissons the following quantities of material were used:

542,000 yds of concrete made from:
236,500 yds of sand
473,000 yds of aggregate
170,400 tons of cement
49,170 tons of reinforcing steel

These figures do not include the immense amount of excavation, concrete, brick, steel, timber and other materials required for making and lining the basins, the formation of temporary dams and basin exits, the construction of building berths, slipways, scaffolding, etc., all of which, with the necessary labour, had to be found, transported and fabricated in a time of unprecedented shortage, and the floating structures completed in six months. (1)

(1) Cyril Raymond James Wood, "Phoenix", The Civil Engineer in War Vol. 2, Institute of Civil Engineers, London, 1948, p. 356.

The costs of the units went as high as 30 pounds per ton.[1] Using 30 pounds/ton as the cost, the average cost/lineal foot was 712 pounds/foot or $2,850/foot at the 1944 exchange rate.

On D-Day, June 6, 1944, the ports began to take shape. The blockships steamed into location, and with the help of tugs, positioned themselves and were scuttled. The Bombardons were providing some shelter by D+2. By D+6 two miles of Bombardons were in place. The placing of the Phoenix units was handicapped by the availability of towing tugs. The actual placing of a unit after it had been brought into the harbor by an ocean tug took only about 90 minutes of which about 16 minutes were all that were required for the actual sinking of the caisson.

On June 18 a storm, that was unprecedented for that time of year, broke and lasted three days. The wind blew at gale force starting in from the NW and shifting around to the NNE. The waves built up to a height of 15 feet and a length of over 300 feet. The storm ruined the American harbor at Saint Laurent. The Phoenixes in the NW part of the harbor were not yet in place, and, therefore, the piers were so badly damaged by the storm that it was decided not to rebuild them. The breakwater was finished after the storm, and the beach was used thereafter for the landing of small craft. The British harbor at Arromanches was more protected. It was badly damaged also, but was repairable.

During the early days of the invasion the Bombardons

(1) D. H. Little, "Discussion on Mulberry Components", <u>Civil Engineer in War</u>, Vol. 2 Institute of Civil Engineers, London 1948, p. 442.

and blockships provided calm water for the hundreds of craft in the landings. The Bombardons withstood winds up to force 5 and 6 and reduced the wave heights by 50% and wave energies by 75%. The Bombardons withstood the storm for 19 hours before they were finally torn loose from their positions by waves which created stresses in the mooring system more than 8 times that created by the design wave. (1) When the Bombardons did break loose they did a great deal of damage to the port as they were tossed around in the harbor by the waves.

The blockships and caissons also suffered heavily during the storm. The scouring action of the waves took away the supports under both ends of the ships and units until the cantilever action was too great and their backs broke. This was especially true at Saint Laurent where the bottom was softer.

The breakwaters were completed and reinforced with other caissons where needed. The harbors did serve their purpose well. Figure 11 is a plan view of the harbor at Arromanches on D+71. As a matter of interest some of the caissons were raised after the war and used for port construction in other places; and some were used to close the dikes in the Netherlands after the big storm and flood of 1953.

There are decided limitations and disadvantages to both of the fabricated types of breakwaters used at Normandy. During the invasion studied, the bases for operation were comparatively

(1) Lochner, Faber and Penny. p. 270.

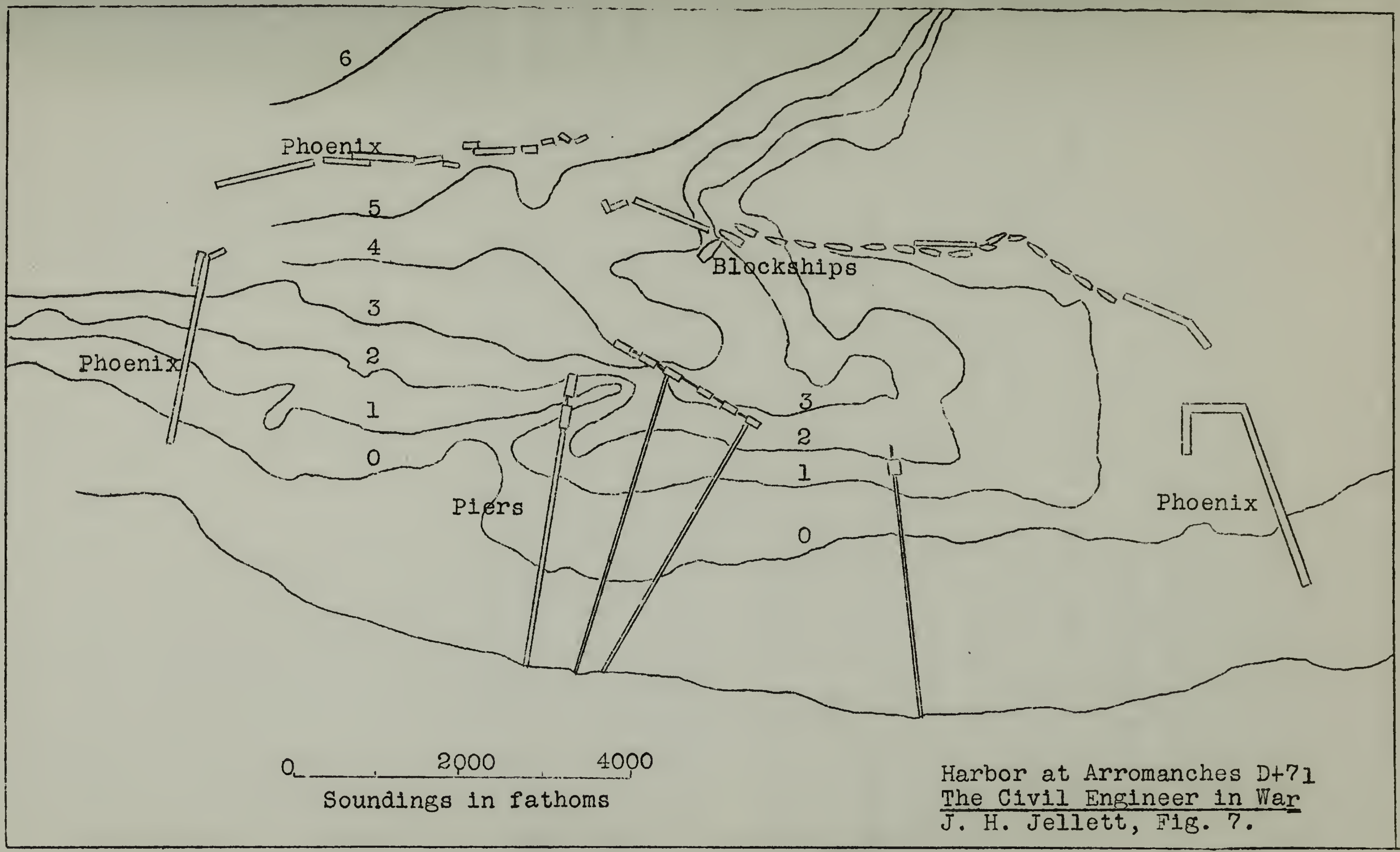

6
5
4
3
2
1
0
Phoenix
Phoenix
Phoenix
Blockships
Piers
3
2
1
0
0 2000 4000
Soundings in fathoms
Harbor at Arromanches D+71
The Civil Engineer in War
J. H. Jellett, Fig. 7.

Figure 11

close to the invasion beaches. Hence the problem of towing the units, although it did delay the establishment of protection, was not critical. A decision was made to use caissons for the invasion of Japan also. This, of course, was not implemented, but it is easily seen what a huge towing effort would have been required. Both of these types of breakwaters were extremely expensive in labor, materials, and building sites, all of which are in short supply during periods of war. Additionally, the depth of water is a limit to the location of the Phoenix, as it would be impractical to construct one for use in water much deeper than the water at high tide at Normandy. The Bombardon is limited to a location where the bottom offers a firm anchorage.

The engineers responsible for the harbors at St. Laurent and Arromanches did a remarkable job in tackling and solving the problem of wave protection in such a short time. The above statements on the limitations of the Phoenixes and Bombardons are not meant to detract from the fact that they did serve their purpose well.

CHAPTER IV

HISTORY, THEORY, AND RESULTS OF PNEUMATIC BREAKWATERS

The history of the pneumatic breakwater is compacted nto a little more than a half century. In 1902 the Parkway Amuse-ent Company built a $125,000 jetty at Brighton Beach, New York, to rotect its waterfront property. Shortly after it had been completed storm battered and destroyed $10,000 worth of it. Philip Brasher, ho was employed by the company, realized the risk in rebuilding the etty and sought a more permanent and less costly solution to the roblem of wave protection.

Having played football and worked as a cowboy, he knew hat a fullback or a steer could be easily brought to the ground ith a minimum of energy by tripping or tackling him close to the round. The thought came to him that possibly wave motion could lso be stopped, while it was still in a deep water stage, by the use f compressed air. The rising air from a perforated pipe on the ottom would intersect the wave motion, changing the direction of he particles in their orbits to the extent that the wave would lose ontinuity and collapse. (1)

Brasher was unable to solve the theory behind the neumatic breakwater and entered Princeton University in search of he additional knowledge necessary. The Dean of Engineering helped im in many ways, and experiments were conducted in the University

1) Robert G. Skerrett, "Smashing Angry Seas with Bubbles of Compressed Air", <u>Compressed Air Magazine</u>, January, 1921, p. 9923.

swimming pool. The theory of the breakwater still eluded him, but he had made enough tests to apply for and receive a basic patent on the idea.

Mr. Brasher employed the breakwater on many occasions, the most recent one being in 1929. A couple of his installations are especially interesting. The U.S.S. Yankee ran aground in a heavy fog upon the rocks on Hens and Chickens Reef near Cuttyhunk, Massachusetts. The salvage of the Yankee was hampered by the exposed position of her grounding, and the waves kept grinding her more and more on the rocks. Brasher proposed a pneumatic breakwater to reduce the effect of the seas during the salvage operations. The installation was made with the air being supplied by the Yankee's own air compressors. The breakwater was very helpful in reducing the wave action on the ship. The publicity for the breakwater did not materialize, however, as the Yankee later sank while being towed into port. (1)

In 1915 Brasher placed a pneumatic breakwater to protect a 2100 foot pier at El Segundo, California. The pier had originally been 4100 feet long, but a storm five years previously had ruined the outboard 2000 feet of it. Figure 12 is a sketch of the installation at El Segundo.

In January 1916 shortly after the breakwater had been finished, a storm, similar to the one that had previously destroyed the outboard end of the pier, raged for 23 hours while the break-

(1) Ibid, p. 9924.

water was operating. The breakwater sufficed to reduce the energy of the waves, and no damage was done to the pier.

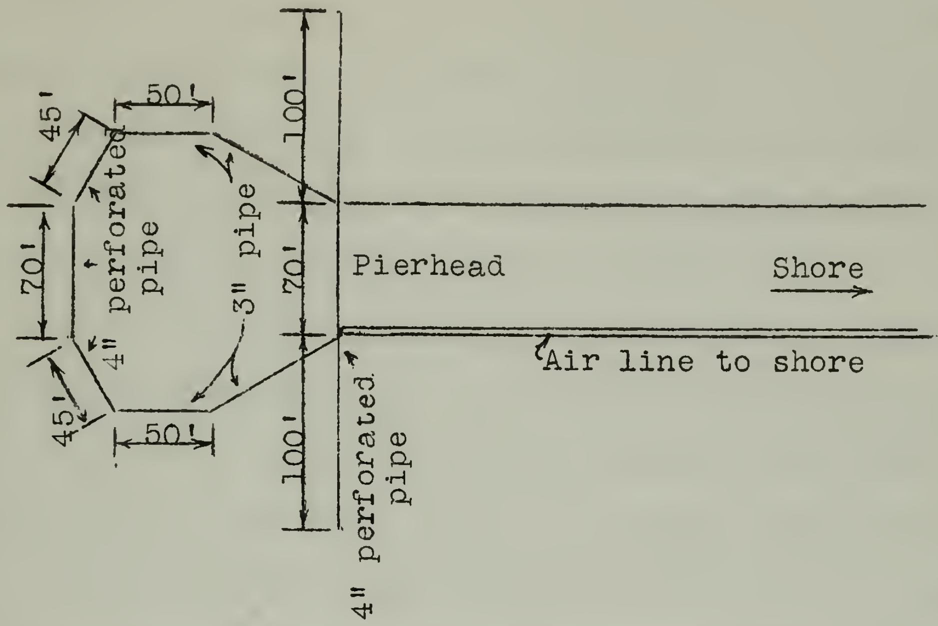


Figure 12. The Breakwater Installation at El Segundo

From Compressed Air Magazine, January, 1921, p. 9925

Unfortunately, Mr. Brasher was unable to obtain quantitative data on the wave length and on the reduction of wave height. This information would have been helpful in later analysis of the breakwaters. He did gather affidavits from witnesses stating in a qualitative way the effectiveness of the particular installation.

Although Mr. Brasher's concept as to the operation of pneumatic breakwaters has not been completely substantiated, credit must be given to him for his conception of the idea and the stimulus that his breakwaters have given the world in adding to the knowledge on the subject.

No other installations or tests were made on the breakwater until 1924 when the English Admiralty Experiment Works conducted model tests with waves 5 to 40 feet long and 6 inches high. The studies showed that the method apparently did accelerate the breaking of the waves but did not elaborate on how this might be done. (1) The report concluded that the breakwater would be effective in exposed shallow coastal waters. (2)

The Central Scientific Research Institute for Water Transport, Leningrad conducted tests on the pneumatic breakwater during the 1930's. These tests were conducted with waves 17 - 20 cm. high, with an L/H ratio from 7 - 10 and a depth of water of 2.4 meters. The reported reduction was 70-100%. (3) It must be noted that these waves are close to the steepness ratio of 1/7 when waves theoretically break with no outside assistance; additionally, the depth of water during these tests was such that the ratio of wave length to water depth was 0.5. For similar conditions in practice the depth of water would have to be 200 feet to stop a wave of 100 feet wave length. This is impractical.

(1) J. T. Evans, "Pneumatic and Similar Breakwaters", Proceedings of The Royal Society, Vol. 231A, London, 1955, p. 458, from M. D. Payne, Admiralty Experiment Works, No. 17/1925.

(2) J. T. Evans, Proceedings of The Royal Society, p. 458.

(3) Walter Hensen, "Model Tests with Pneumatic Breakwaters", Dock and Harbour Authority, June, 1955, London, p. 60.

J. Th. Thijsse of Delft experimented in 1936 with the pneumatic breakwater. His experiments contributed greatly to the advance of knowledge. He proposed that the feature of the breakwater that actually calmed the water was not the air itself but the water currents that were set in motion by the air. (1) The water currents rise vertically as in an air lift pump and then spread out horizontally when they reach the surface. He concluded that the volume of air required to produce any results would have to be very great.

J. B. Schijf wrote in 1940 of his model experiments on the pneumatic breakwater. (2) He expressed a relationship between the quantity of air required for wave reduction and the length and height of waves, by means of a dimensionless term. The quantities of air that he estimated would be needed to stop waves, were several hundred times greater than the actual volumes of air used in full size installations. He concluded that there must be a scale coefficient between models and actual practice that had not yet been discovered. (3)

In 1942 P. J. Unna studied the effect of the tidal currents on ocean waves at their intersections. Unna showed the

(1) Evans, Royal Society, p. 458.

(2) J. B. Schijf, "Het vernietigen van golfen door het inspuiten van lucht (Pneumatische golfbrekers)", De Ingenieur, 1940.

(3) Hensen, p. 60.

relationship as follows:

$$T = \frac{L_o}{C_o} = \frac{L_2}{C_2} = \frac{L_2}{C_r - C_c}$$

where C_c is the velocity of the tidal current meeting a wave, L_2 is the wave length due to the new conditions of wave form, and C_r is the velocity of the wave relative to the current.

$$C_r^2 = \frac{gL_2}{2\pi} \tanh \frac{2\pi d}{L}$$

$C_2 = C_r - C_c =$ the velocity of the wave relative to the ground.

$$\frac{L_o}{C_o} = \frac{L_2}{C_r - C_c}$$

$$\frac{C_o^2 \frac{2\pi}{g}}{C_o} = \frac{C_r^2 \frac{2\pi}{g} \operatorname{cotanh} \frac{2\pi d}{L_2}}{C_r - C_c}$$

$$\frac{C_r^2 \operatorname{cotanh} \frac{2\pi d}{L_2}}{C_o} - C_r + C_c = 0$$

$$\frac{C_r}{C_o} = \frac{1}{2} - \sqrt{\frac{1}{4} - \frac{C_c}{C_o}}$$

When the current velocity is 1/4 the deep water wave velocity, $C_r = 1/2 \; C_o = 2 \, C_c$. Inasmuch as wave energy travels in deep water at 1/2 the wave velocity the velocity of the energy is equal to C_c, and therefore, there can be no transmittal of wave energy relative to the ground. Consequently, a deep enough opposing

surface current with a velocity equal to one-fourth the wave velocity is a 100% effective breakwater. Unna also stated that an opposing surface current would shorten the wave length and increase the wave height giving the waves more of a tendency to break. (1)

Sir Geoffrey Taylor studied the pneumatic breakwater for the British Admiralty in 1942 from a theoretical viewpoint. He believed, as did Thijsse, that the sole purpose of the compressed air bubbles was to create the vertical water currents, and consequently, the horizontal ones, which were ultimately responsible for the reduction of the waves.

Taylor's work showed that there was, for any given velocity and depth of surface water currents, a critical wave length. All waves shorter than this wave length would be stopped by the surface currents. The critical velocity can be found for two cases. Case 1 is for a current that has a uniform velocity to a depth h.

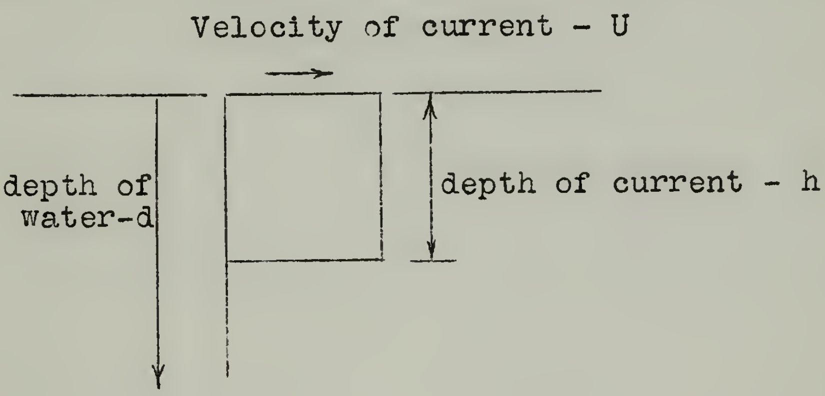


Figure 13. Case 1 - Taylor

(1) P. J. Unna, "Waves and Tidal Streams", Nature, Vol. 149, February 21, 1942, London, p. 219.

For a wave with a length $L = 2\pi/k$ and a frequency $= \sigma/2\pi$ the critical wave length is a function of three parameters:

$$Y = \frac{kU}{\sigma}, \quad \alpha_1 = \frac{g}{U\sigma} \qquad Z = \frac{hg}{U^2}$$

where U is the velocity of the horizontal current, g is the acceleration due to gravity, and h is the depth of horizontal current. Figure 14 shows the relationship between the parameters.

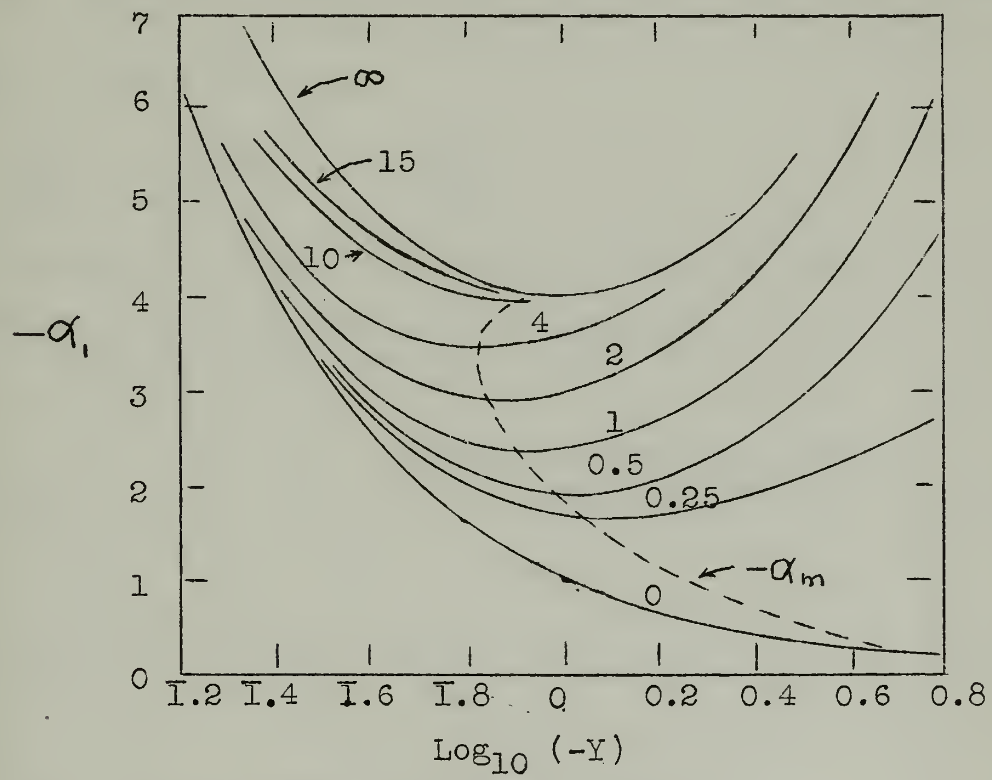


Figure 14. Lines of Constant Z for Case 1.

G. I. Taylor, "Action of Surface Current Used as a Breakwater", Proceedings of the Royal Society, London, Vol. 231A, p. 470.

It is to be noted that there is a minimum value of $-\alpha_1$, α_m, for any value of Z therefore no wave with a frequency greater than $\sigma/2\pi = -\frac{g}{2\pi U\alpha_m}$ can be propagated against the current. In deep

water the wave length of this critical wave can be found from the relationship:

$$C^2 = \frac{gL}{2\pi} \qquad C = \frac{gT}{2\pi} = \frac{g}{2\pi\frac{\sigma}{2\pi}} = \frac{g}{\sigma}$$

$$L = \frac{g^2}{\sigma^2}\frac{2\pi}{g} = \frac{2\pi g}{\sigma^2} = \frac{2\pi g}{\frac{g^2}{U^2\alpha_m^2}} = \frac{2\pi U^2\alpha_m^2}{g}$$

To determine the velocity of surface currents necessary to stop a wave of a specified length, L_o, the equation for the critical wave length can be transformed to:

$$\frac{L_o}{2\pi h} = \frac{U^2\alpha_m^2}{gh} = \frac{\alpha_m^2}{Z}$$

The relationship between α_m and α_m^2/Z is shown in Figure 14 but is more readily seen when plotted as in Figure 15.

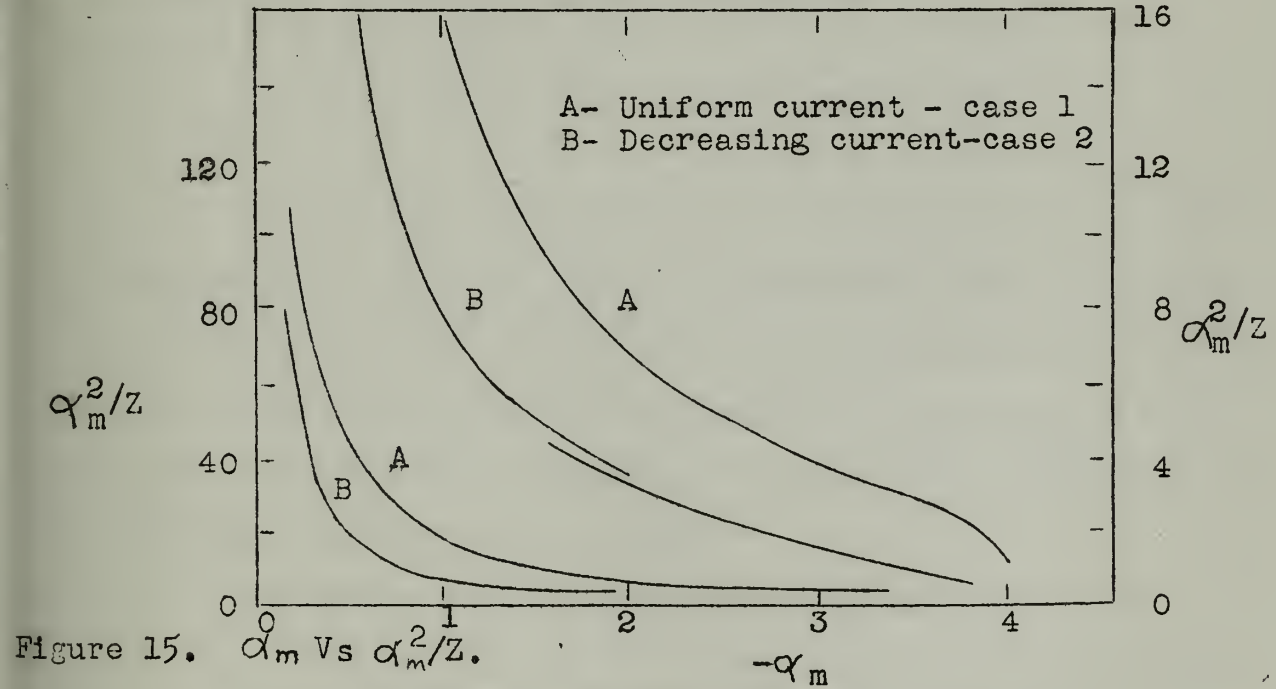


Figure 15. α_m Vs α_m^2/Z.

G. I. Taylor, "Action of Surface Current Used as a Breakwater", Proceedings of the Royal Society, London, Vol. 231A, p. 472.

The value of α_m^2/Z can be found knowing L_o and h. Knowing α_m^2/Z, $-\alpha_m$ is found from Figure 15, and the current necessary to stop the wave is

$$U = \frac{-1}{\alpha_m} \sqrt{\frac{g\, L_o}{2\pi}}$$

Case 2 is for a current that decreases linearly with depth. (Figure 16.) This case was studied after Mr. J. T. Evans had shown in 1955 that the surface currents followed this pattern rather than Taylor's original assumption, Case 1.

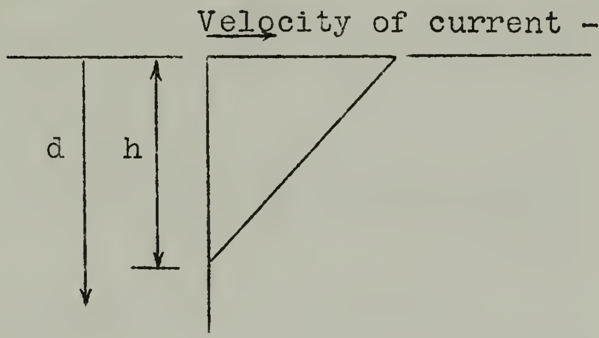


Figure 16. Case 2 - Taylor.

For case 2 the parameters and equations are the same as for Case 1, but the relationship between the parameters (See Figure 17) is different. When Y is small the graphs are accurate enough for the determination of α_m and Z ; however, as $-Y$ increases it is increasingly difficult to find them graphically and the following table becomes helpful.

Asymptotic formulae valid for large values of $-Y$

	Uniform current	Current decreasing with depth
α_m	$3/2Y$	$3/2Y$
Z	$3/4Y^4$	$9/4Y^4$
$\frac{\alpha_m^2}{Z}$	$3/Y^2$	Y^2

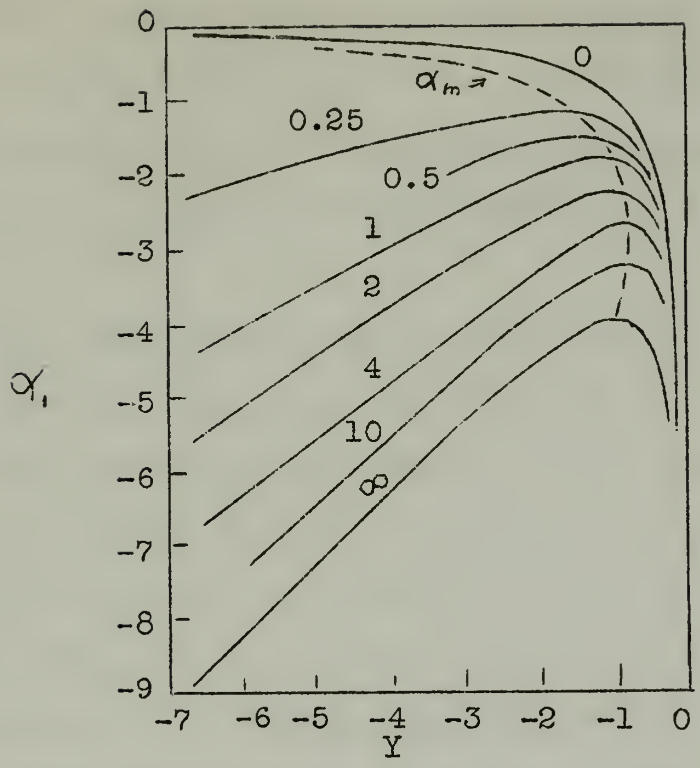


Figure 17. Lines of Constant Z for Case 2.
From G. I. Taylor"Action of Surface Current Used as a Breakwater", Proceedings of the Royal Society, London, Vol. 231A, p. 474.

Taylor also studied the surface currents that could be generated by compressed air being released under water. He reasoned that if the weight of the air bubbles is neglected in comparison to the weight of the water they displace, the air gives to the water the same buoyancy that a rise in temperature gives to air. Currents above a line source of heat were worked out by W. Schmidt. (1) He showed that the heat spread out linearly as in a wedge. The half angle of the wedge is arctan

(1) Schmidt, W., Z Angew Math. Mech. Vol. 21, p. 265.

0.28, and the vertical rise is proportional to the cube root of the heat supplied. Taylor's analogy to the rise of currents due to the release of air in water showed W = 1.9 $(Qg)^{1/3}$. If it is assumed that there is no loss of energy, the horizontal currents produced would have a velocity of 1.9 $(Qg)^{1/3}$ and a depth of 0.28z. (1)

In the early days of WWII the severe range in the Port of Madras made berths in the port untenable for two or three days at a stretch. This was very unfortunate as the rapid turn around of ships was vital due to the Allied shortage of shipping. It was decided to try a pneumatic breakwater across the entrance to the boat basin. The entrance was 80' wide and 20' deep. The arrangement consisted of a 3" pipe, anchored on the bottom, with 1/2" diameter holes spaced every 6". Air was supplied by a compressor with a capacity of 300-400 cfm.

The breakwater was successful in damping short waves, but the results with waves due to cyclonic storms were inconclusive. It was decided not to repeat the experiment at the main entrance to the harbor where the width was 400' and the depth of water was 33', as the necessary compressor would have been too expensive. (2)

In 1949 the Bureau of Yards and Docks, U. S. Navy, contracted with the Hydrodynamics Laboratories of the California

(1) Taylor, p. 478.

(2) P. R. Robinson, for Rendel, Palmer, and Triton Engineers, letter to the author, March 4, 1957.

Institute of Technology for the study of the mechanism of wave reduction by a pneumatic breakwater.

Dr. L. I. Schiff of Stanford University, who is a consultant of the Laboratories, made an analytical study of wave reflection due to the aerated zone created by the pneumatic breakwater. (1) Schiff found that even with a large volume of air released the change in wave velocity was only about two percent. Further, he showed that if it were possible to maintain the aerated zone for the width of one-half wave length the height of the wave would be reduced only by one-half of one percent. Furthermore, only 2 1/2% of this reduction is due to the compressibility of the bubbles, the rest being attributed to a change in density. If the volume of air used in this one-half wave length wide zone was split up into ten zones, one-half wave length apart, the wave amplitude would be decreased by 27%, a promising figure, however, if the wave length changed slightly the spacing of the zones would be wrong for the new length. As the tolerance in the spacing of a ten zone breakwater is ± 1% the scheme is impractical. (2)

Mr. Marvin Gimprich of Stevens Institute of Technology in connection with Schiff, extended the work of Taylor to include shallow water waves. Their results showed that, inasmuch as the

(1) L. I. Schiff, Air Bubble Breakwater, Report No. N-74, 1, Hydrodynamics Laboratories, California Institute of Technology, Pasadena, California, 1949.

(2) John H. Carr, Mobile Breakwater Studies, Report No. N-64-2 Hydrodynamics Laboratories, California Institute of Technology, Pasadena, California, 1950, p. 21.

orbits of these waves extend all the way to the water bottom, the surface currents would have less effect on them than on the deeper waves.

Dr. John H. Carr, of the Hydrodynamics Laboratories, conducted model studies of the pneumatic breakwater in order to study the effects of the breakwater. Carr studied the effect on the damping of waves of the relationship between the wave length and the depth of water and the effect of varying the amount of air emitted. Figure 18 shows the results of the study.

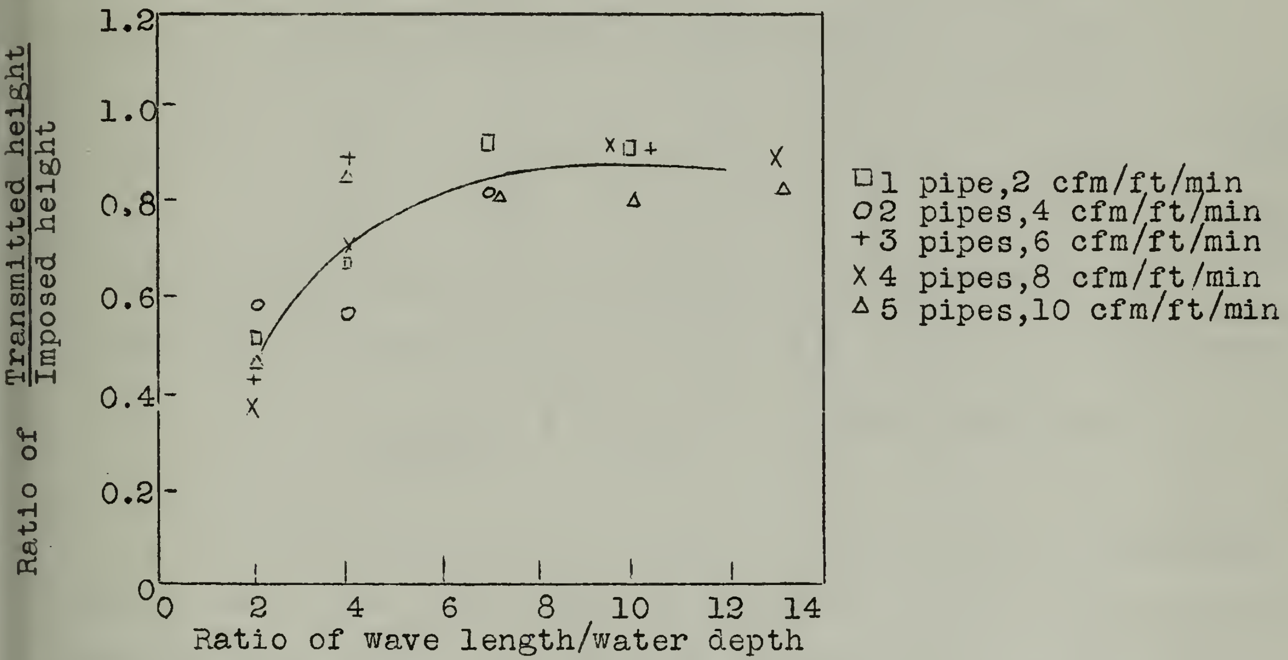


Figure 18. The effect of the depth of water and varying the amount of air emitted on wave dampening.

Dr. John H. Carr *Mobile Breakwater Studies* . P. 23.

The effectiveness of the breakwater dropped rapidly as the relative depth of water shifted from deep water to shallower water; there-

fore, if the breakwater is to be successful it must be placed in water which is at least as deep as 1/3 the length of the design wave, and deeper if possible.

Tests were made confirming Taylor's work on the velocity of surface currents (Figure 19.) The tests show that the increase of the velocity of the surface currents, with an increasing volume of air, is approximately proportional to the cube root of the ratio of the volumes of air emitted, as predicted by Taylor.

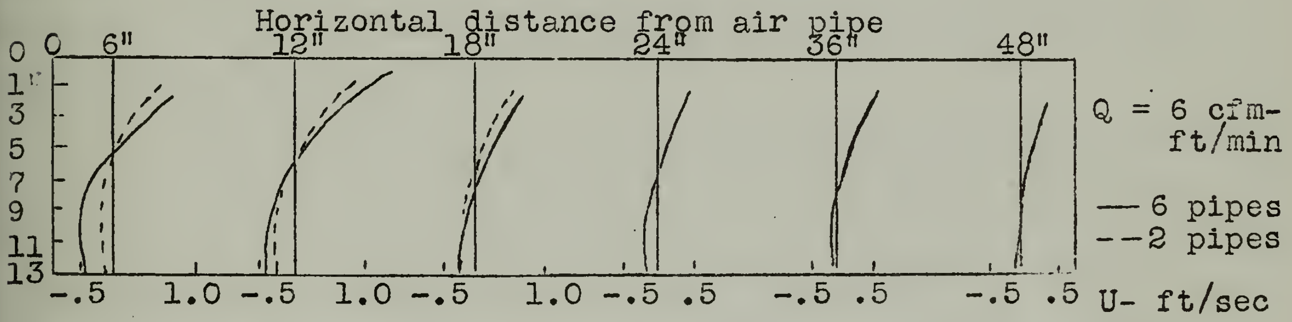


Figure 19. The variation of current with depth and displacement.

Dr. John H. Carr Mobile Breakwater Studies . P. 20.

An investigation was made of the effect of replacing the air pipe with water jets. The results obtained with the water jets were very nearly equal to those obtained with the air pipes.

Carr concluded that the breakwater would be effective if the ratio of L/d is less than 3. For ocean waves with periods of 10-15 seconds (length 512-1152'), the L/d ratio in 50' of water would be 10 or greater, and therefore, the pneumatic breakwater is not a promising method of wave reduction. (1)

(1) Carr, p. 26.

In the fall of 1952, Mr. A. H. Laurie constructed a pneumatic breakwater in the harbor of Dover, England. This breakwater was to protect the inner gate of a train ferry dock from waves while the outer gate was removed for overhaul. The breakwater consisted of four parallel pipes resting on the bottom across the dock entrance. (It was found that one pipe would have been sufficient to have done the job.) The breakwater was used on 22 occasions during the three months it was needed. The dock was usable during the entire period. On 5 or 6 occasions the waves were of such nature that the dock could not have been used without the breakwater. (1)

The installation at Dover stimulated the English Dock and Inland Waterway Research Station, Mr. J. T. Evans directing, to investigate the conditions under which the pneumatic breakwater could be economically used in practice. Model studies were conducted in a wave tank that was 4' deep, 4' wide, and 62' long using a normal depth of water of 3'.

Evans experimented using a perforated pipe and a porcelain filter. The pipe had 150 holes of 11/16" diameter in the 4' long section, and the filter had thousands of microscopic holes. The difference in the diameter of the air bubbles could not be visually noted, and the surface currents differed by less than 10%.

(1) J. T. Evans, "Pneumatic and Similar Breakwaters", Dock and Harbour Authority, December, 1955, London, p. 251.

Inasmuch as the only function of the air is to create the water currents, Evans experimented by replacing the air pipe with water jets. Where Carr placed his water jets on the bottom pointing upwards, Evans placed his jets one foot below the surface with an inclination upwards of about 12°. It was found that the jets could match, in effect, the currents created by the air pipe. For each matched condition, the power supplied to the compressor motor was approximately the same as the power supplied to the pump motor.

The water in the lee of the jet breakwater was found to be completely calm, while the water behind the pneumatic breakwater always had a residual disturbance due to the half of the vertical current that flows in the direction of the wave motion. therefore, it appears that it would be better to forget the pneumatic breakwater and to develop the water jet breakwater. Theoretically that may be correct. Practically, however, the problem of mooring the water pipe in place to resist the thrust of the jets rules out its use. With the pneumatic breakwater the thrust is negligible.

Evans continued his experiments using the water jet breakwater as the effects were similar, and he had more power available with the jets.

The velocity of the surface currents required to stop a wave was found to be a function of the length and height of the wave, the depth of water, and the thickness of the horizontal currents.

Figure 20 shows the relationship between the stopping velocity of the horizontal current and the ratio of the wave length to the depth of water.

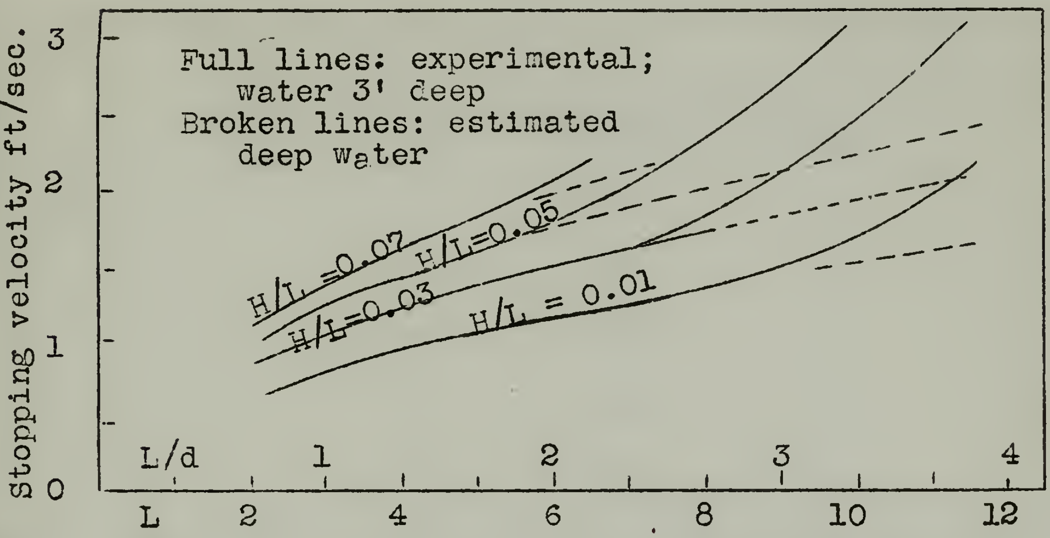


Figure 20. The effect of wave length on stopping velocity.

J. T. Evans, "Dock and Harbour Authority," December, 1955, p. 253.

Table 4 shows the same information, for deep water waves only, and also the horsepower required for complete calming of the waves.

Height / Length Ratio	Stopping velocity of horizontal surface current L/10 thick, in deep water. Mean velocity of current feet/second at position of maximum velocity reached in its course	Horsepower contained in opposing current of thickness L/10 to calm waves completely Horsepower/lineal foot of wave crest.
0.01	$U = 0.50\ L^{1/2}$	$0.29\ L^{2.5} \times 10^{-4}$
0.03	$U = 0.62\ L^{1/2}$	$0.55\ L^{2.5} \times 10^{-4}$
0.05	$U = 0.73\ L^{1/2}$	$0.90\ L^{2.5} \times 10^{-4}$
0.07	$U = 0.83\ L^{1/2}$	$1.31\ L^{2.5} \times 10^{-4}$

Table 4. The effect of wave length on stopping velocity and power.

J. T. Evans, Dock and Harbour Authority, December, 1955, p.253-4.

It was shown by Carr that the power required to calm waves increases with the ratio of L/d when the ratio exceeds 2.0. Table 5 gives the increase in horsepower required for wave reduction as the deep water requirements are modified by shallower water.

Length Depth Ratio	Factor giving stopping horsepower in shallow water. Surface current L/10 thick.		
H/L	0.01	0.03	0.05
2 or less	1.0	1.0	1.0
2.5	1.0	1.1	1.3
3.0	1.2	1.6	2.1
3.5	1.6	2.3	3.0
4.0	2.4	3.4	4.0

Table 5. The effect of the ratio of L/d on the stopping horsepower.

J. T. Evans, <u>Dock and Harbour Authority</u>, December, 1955, p. 254.

As shown on page 16 the energy in a wave is proportional to the square of the wave height; therefore, if the height can be reduced 50% the transmitted energy will be only 25% of the original wave energy. In many applications complete calming of waves is not necessary or possible with the equipment available. Table 6 shows the horsepower required for partial calming of the waves as a percentage of the horsepower necessary for complete annihilation of the waves. Note that with steep waves it is possible to take away 3/4 of the energy in the wave with only 1/4 of the power necessary for complete wave reduction.

Height/Length Ratio	Horsepower required to lower waves to heights shown, expressed as percentages of the horsepower required to stop the waves completely. Surface current L/10 thick			
	Residual height of wave as fraction of initial height			
	0	1/4	1/2	3/4
	Residual wave energy as fraction of initial energy			
	0	1/16	1/4	9/16
0.01	100	86	72	37
0.03	100	64	44	20
0.05	100	48	30	13
0.07	100	42	23	10

Table 6. The effect of partial reduction on the power required.

J. T. Evans, Dock and Harbour Authority, December, 1955, p. 254.

The relationship between the power in the surface current and the reduction in wave power due to the current varies with the H/L of the wave and the amount of wave reduction. With an H/L ratio greater than 0.04 and with partial reduction of the waves, more energy is dissipated in the wave than is contained in the surface current; however, the horesepower required to produce the surface current is approximately seven times the horsepower in the current. No evidence was found that the reduction in wave energy was more than the applied energy. Table 7 shows the results of this study.

Height/Length Ratio	Reduction in wave horsepower, expressed as % of the horsepower in the opposing current. Surface current L/10 thick; deep water condition Residual height of wave as fraction of initial height: 0	1/4	1/2	3/4
0.01	5	6	6	6
0.03	26	37	44	57
0.05	46	87	114	153
0.07	62	139	193	273

Table 7. The reduction of the horsepower in a wave vs. the horsepower in the surface current.

J. T. Evans, <u>Dock and Harbour Authority</u>, December, 1955, p. 255.

Evans experimented with jets at various positions and obtained currents of different thicknesses. The stopping velocity of the opposing current and the horsepower in the current changed considerably with the different depths as shown in Table 8.

Thickness of surface current as % and as fraction of wave length		Stopping velocity as % of Wave velocity	Relative values of stopping horsepowers in surface currents
2.5	L/40	45.5	172
4.2	L/24	34.5	113
5.0	L/20	31.0	100
10.0	L/10	26.5	126
14.0 or thicker	L/7	25.0	152

Table 8. The effect of the current thickness on the efficiency of a breakwater.

J. T. Evans, <u>Dock and Harbour Authority</u>, December, 1955, p. 255.

It is to be noted that a depth of surface current equal to L/20 is the most economical. In breakwater design, therefore, the depth of current should be regulated to L/20 of the wave length. Table 9 shows the energy in waves of different sizes and the power required to stop or reduce it. The power required increases with the length and the height of the wave, especially in the case of complete reduction; however, as the energy in the wave builds up much more rapidly, the benefit to be gained by the breakwater for each horsepower invested, is greater with higher and longer waves.

Wave Length Feet	Wave Height Feet	Energy in a wave Ft-Lbs/Ft of crest(1)	Horsepower per foot run of wave crest required in the opposing current to produce the following effects. Residual height of wave as % of initial height. 0 / Residual energy as % of initial energy 0	25% / 6%	50% / 25%	75% / 56%
100	1	800	3.0	2.6	2.2	1.1
	5	20,000	9.0	4.3	2.7	1.2
150	1.5	2,700	8.0	7.0	5.8	3.0
	7.5	67,500	25.0	12.0	7.5	3.3
	10.5	132,300	37.0	16.0	8.5	3.7
200	6	57,600	31.0	20.0	14.0	6.1
	10	160,000	51.0	25.0	15.0	6.6

Table 9. The energy in certain waves and the horsepower required to reduce it.

J. T. Evans, Dock and Harbour Authority, December, 1955, p. 255.

(1) This column added by author.

The type of wave that is encountered in a range problem, such as at Madras, is a very shallow one with possibly a height of one foot and a length of thousands of feet. The power required to stop such a wave is very large, while the energy in the wave is comparatively small; therefore, a pneumatic breakwater is not an economical means of solving a range problem.

Evans concurred with Unna that a surface current with a velocity equal to one-quarter the wave velocity and sufficiently thick would stop all energy transmission; however, he added that experiments have shown that part of the energy in the wave is dissipated by turbulence and eddies, at the horizontal interface between the current and the still water, without the need for the wave to be raised to the breaking steepness. (1)

In 1954, Dr. Otto Linke at the Franzius Institute, Hanover, Germany, undertook tests with a model pneumatic breakwater to see if the breakwater would protect Heligoland Harbor. The tests were conducted in a tank that was 112 meters long, 2.20 meters wide and with a depth of water of 1.15-1.17 meters. The tank had no wave-damping beach, and consequently, a test was concluded when the reflected waves interferred with the test. The tests indicated that the most important parameter in determining the effectiveness of the pneumatic breakwater was the wave steepness. Figure 21

(1) Evans, Dock and Harbour Authority, December, 1955, p. 255.

shows the wave reduction obtained with various values of steepness.

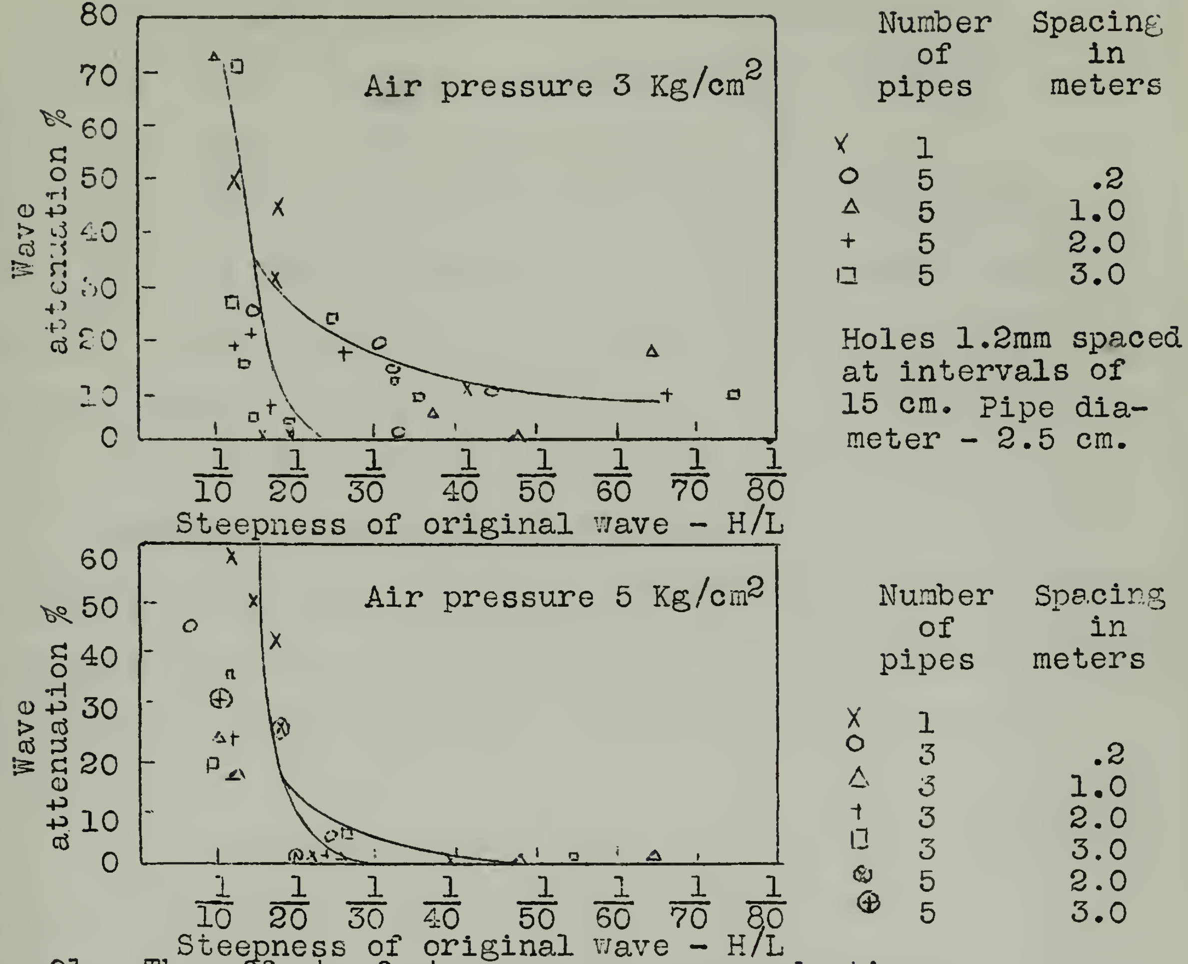


Figure 21. The effect of steepness on wave reduction.

Walter Hensen, Dock and Harbour Authority, June, 1955. p. 58.

With waves that had a steepness (H/L) greater than 0.06 the wave reduction was relatively large. With wave steepness less than 0.05 the attenuation was minor. The fact that steeper waves break more easily than shallow ones is not unexpected in view

of the fact that, as shown on page 15, waves will break when their steepness approaches 1/7; therefore, waves that approach this critical steepness initially will be shortened and heightened to an H/L of 1/7 more easily than shallower waves.

Waves that were substantially reduced broke at the breakwater and formed surf. Those that did not break were reported to be reduced immediately behind the breakwater but later to have regained their height. This was probably due to the surface currents traveling in the same direction as the wave. These currents would tend to lengthen and lower the waves, as the opposite currents shorten and heighten them. When the current dies out, the wave length is shortened to comply with the depth of water; consequently, the wave height is raised to maintain the same wave energy.

The experiments showed that the efficiency of the breakwater is controlled by the volume of the vertical water current. This in turn is controlled primarily by the volume of air and only secondarily by the size of the bubbles. The vertical water currents increase at first with an increase in air pressure, but there is a maximum pressure for each water depth. As the depth of water increases, the effect of increasing air pressure is greater. (1)

Laurie, in commenting on the failure of waves shallower than H/L = 0.05 to be reduced in the Franzius tests, points out that with a wave length of 3.9 meters and a depth of water of 1.17

(1) Hensen, p. 59.

meters the orbit at the bottom of the tank had 1/3 of the motion of the orbit at the surface. With an effective barrier going only part way to the bottom of the tank, much of the energy of the wave passed under the barrier and showed up on the lee side of the breakwater. The size of the orbit, passing immediately under the barrier, is the size of the transmitted wave. (1)

In this connection Laurie proposed one solution to the discrepancy between model studies and full size installations. If the air pipe is placed at a depth of 1/2 wave length, its depth in a tank might be 1 meter; whereas, in an actual installation it might be 20 meters. In the deeper installation the air has a longer time to generate water currents and, therefore, is more efficient; consequently, even though both pipes are at a depth of 1/2 wave length the model is at a great disadvantage.

Laurie took the data supplied by the Franzius Institute and the data from Bogolepoff's tests and replotted them using orbital velocity as an argument and the volume of air as a parameter. (See Figure 22.) This plot clearly shows the limiting effect of orbital velocity in the Franzius tests. For orbital velocities below 1.3 feet per second, the wave reduction is negligible even for the higher volumes of air used. As the orbital velocity exceeds this critical figure, the wave attenuation increases rapidly. If it is supposed that a pneumatic breakwater acts as a finite barrier in a way not yet explained, it is possible to find the effective depth of the barrier by the height of the transmitted wave. Figure 23 is a graph of the amplitude of the orbit at the bottom of

(1) Lockner, Faber, and Penney, p. 275 showed that the amplitude of the transmitted wave is equal to the amplitude of the orbit at the bottom of a finite barrier.

the barrier to the surface amplitude, versus the depth of water. Superimposed on this graph is a plot of relative amplitude of the transmitted waves recorded in the Franzius test for the various volumes of air employed.

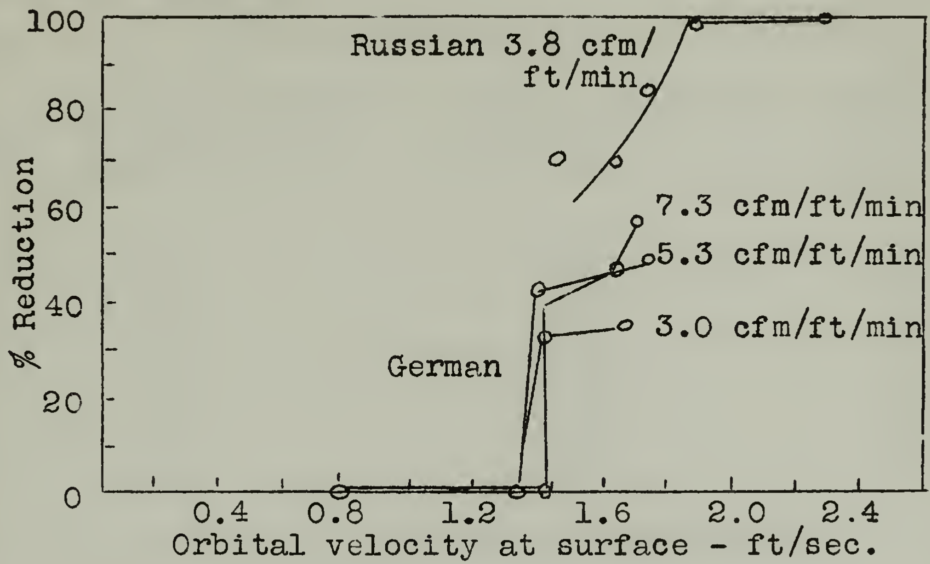


Figure 22. The relationship between orbital velocity and wave reduction.

A. H. Laurie, Dock and Harbour Authority, June, 1955, p. 62.

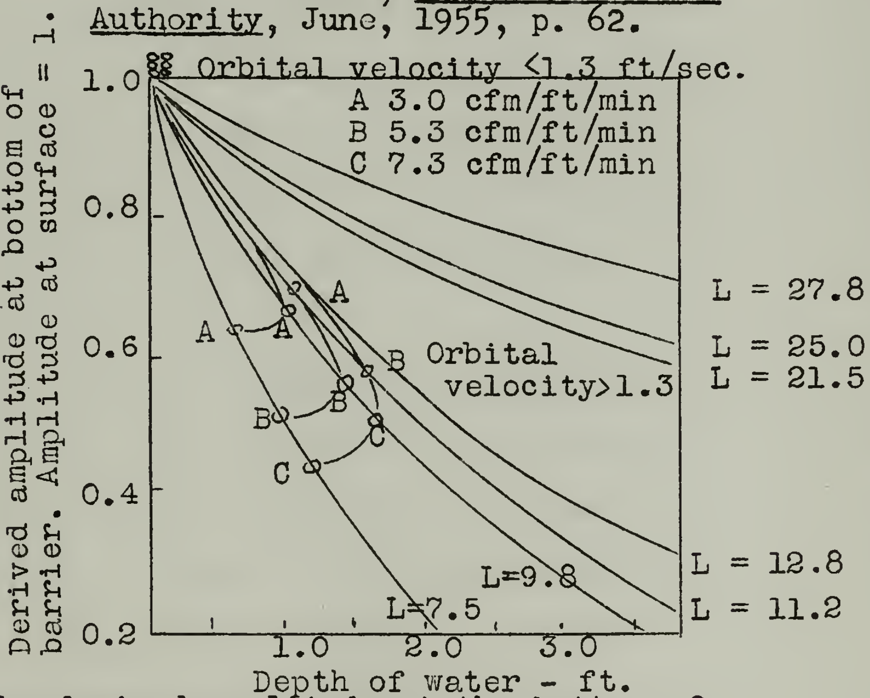


Figure 23. The derived amplitude at the bottom of a pneumatic barrier.

A. H. Laurie, Dock and Harbour Authority, June, 1955, p. 63.

The amplitude of the waves at the surface and at the bottom of the barrier are converted into orbital velocities by using the wave periods and heights. Table 10 shows the orbital velocities at the bottom of the barrier for the different conditions.

Air input cu.ft/ft.min.	Orbital velocity at the surface ft./sec.	Orbital velocity fraction at depth ft. / sec.	Actual orbital velocity at bottom of barrier ft./sec.
3.0	1.64	0.64	1.05
3.0	1.32	0.66	1.02
5.3	1.64	0.51	0.84
5.3	1.32	0.57	0.87
5.3	1.36	0.68	0.93
7.3	1.8	0.42	0.76
7.3	1.6	0.52	0.84
7.3	1.36	0.6	0.81

Table 10. Orbital velocity for different experiments.
A. H. Laurie, Dock and Harbour Authority, June, 1955, p. 63.

For each group of air volumes, the actual orbital velocity at the bottom of the barrier is nearly constant, and this velocity decreases with increasing volumes of air. Laurie submits that this orbital velocity consideration, which is not inconsistent with the facts, may be a clue to the wave reduction mechanism of the pneumatic breakwater.

The Research Institute for Applied Mechanics, Kyushu University, Japan, has done a great deal of research on pneumatic breakwaters. They have made model tests in a wave tank and have installed and tested two separate full size breakwaters. As their full size tests are the first that have been fully recorded and analyzed, they offer valuable information on the action of compressed

air in reducing wave energy.

The first full size tests were conducted during the winter of 1955 at the Iwojima Islands off the Harbor of Nagasaki. The location was chosen because the length of waves encountered there, up to 15 meters, was short enough to insure positive annihilation of the waves. This afforded the Institute a chance to obtain fundamental information on wave annihilation. Figures 24 and 25 show the installation of the first test breakwater.

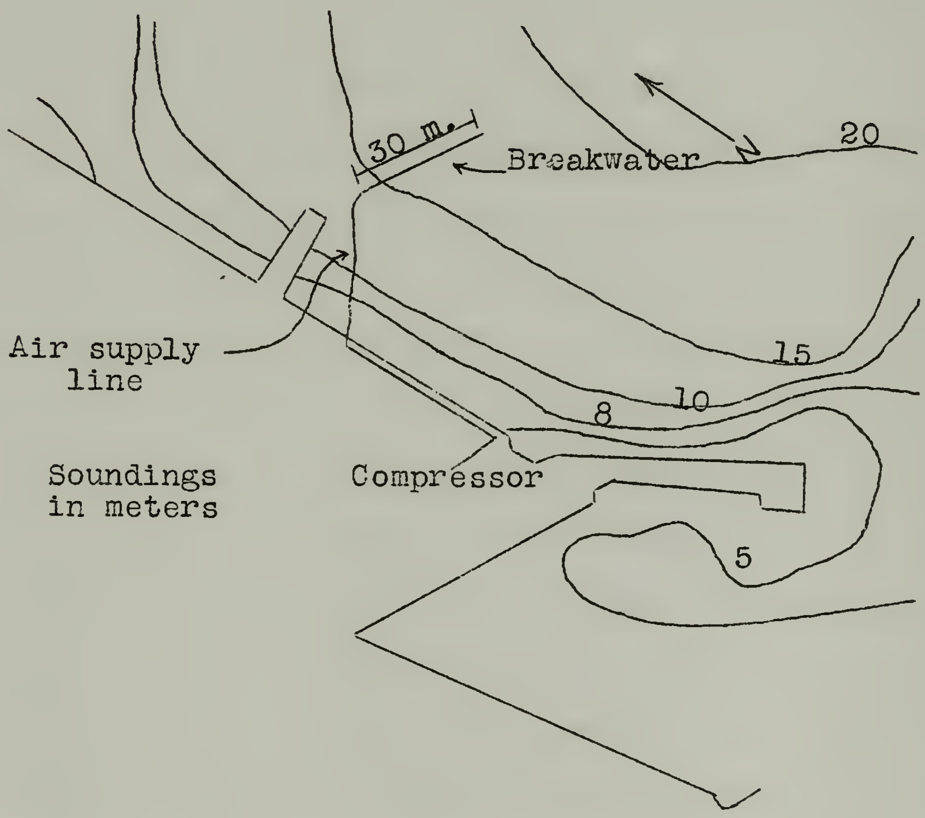


Figure 24. Plan view of breakwater at Iwojima.

Research Committee for Hydrology, On the Study of a Pneumatic Breakwater II, p. 4.

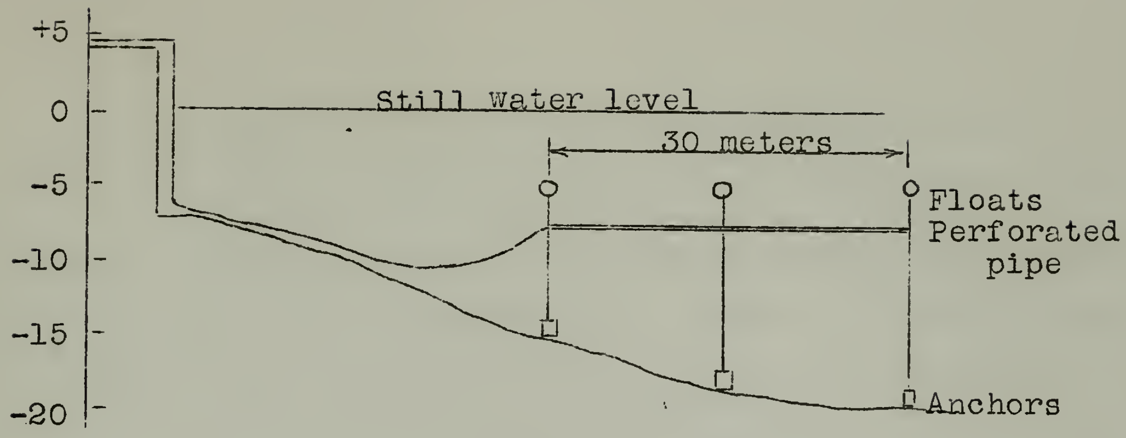


Figure 25. Elevation view of breakwater at Iwojima.

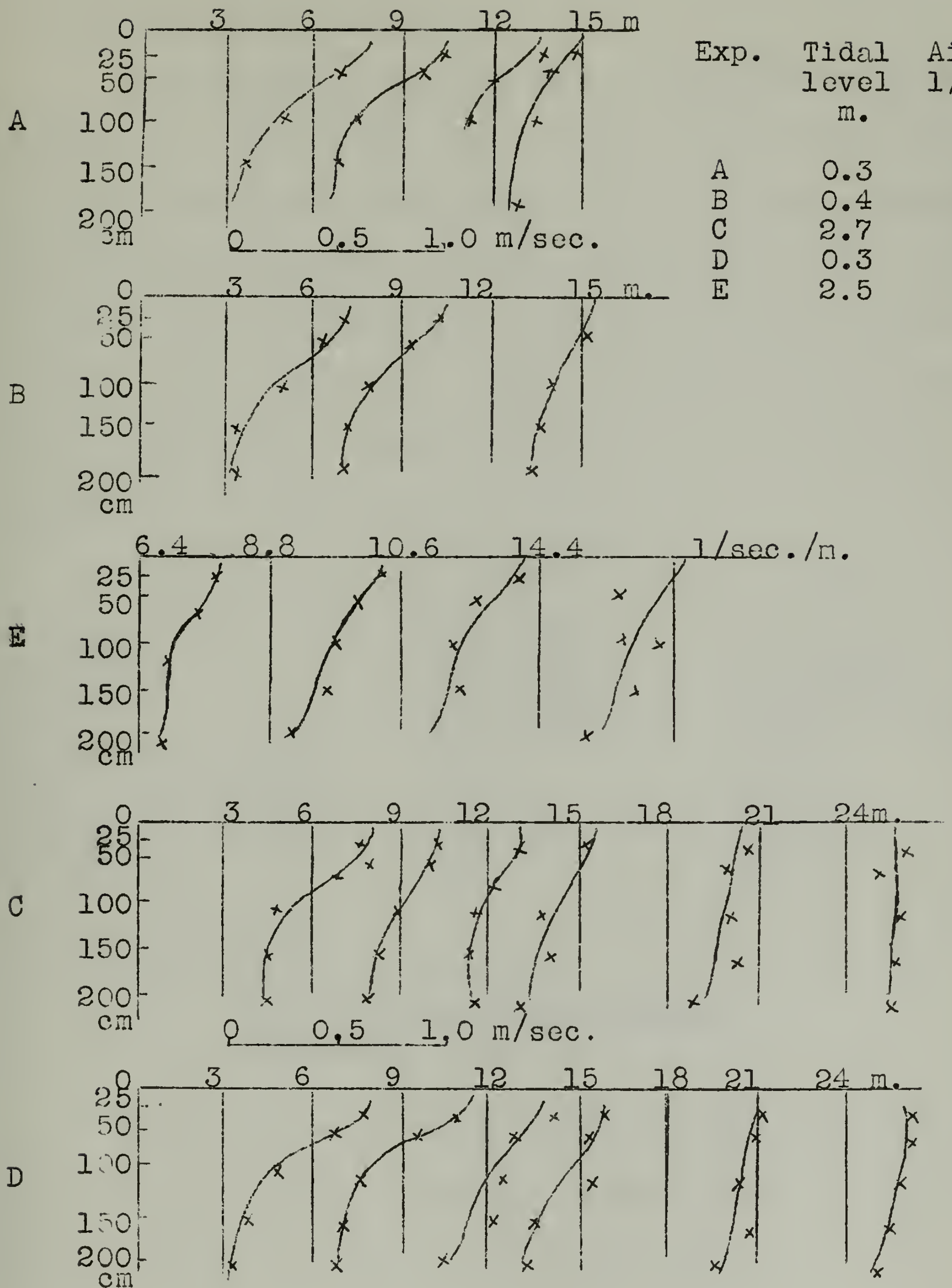
Research Committee for Hydrology, <u>On the Study of a Pneumatic Breakwater II</u> p. 4.

The fetch to the east is two to three kilometers, to the northeast six kilometers, and to the north-northwest ten kilometers. During the seasonal winter, wind waves of 3-4 seconds are encountered from the northeast and longer diffracted waves from the northwest. The design wave for the tests was 15 meters long, (3.1 second period). The 3" diameter air pipe was placed at a depth of 8 meters at lower low water and was 30 meters long, or twice the wave length. The volume of air available was 30 m^3 per minute or 1 m^3/min/m of pipe. It is to be noted that, with a 15 m wave and a depth of water of over 15 m, these tests were conducted with "deep water waves". Previous model studies have shown that deep water waves are easier to subdue than transitional or shallow water waves. It also must be noted that, at a depth of 8 meters, approximately 97% of the wave energy from a 15 m wave passes through the aerated zone.

In the design of the pipe the differential pressure between the pipe and the water was assumed to be $1Kg/cm^2$ and the coefficient of vena contracta 0.6; therefore, 35.7 holes per meter of 1.5 mm diameter were necessary for the volume of air available.

During calm weather the breakwater was operated to determine the velocity of the horizontal currents at various points. Figure 26 shows the results of this investigation. It can be noted from tests B and C that as the level of the tide increases, the air pipe getting deeper, the depth of the current increases. This indicates the relative efficiency of breakwaters at different depths. It also can be noted that the velocity of the current at a distance from the air pipe (x = 24m and x = 3m for tests C and changes little with depth, while close to the pipe the velocity gradient is steep.

A derivation of the relationship between the velocity of the water currents and the volume of air, indicated that $U \propto Q^{1/3}$. This relationship agrees with the work of Taylor and was confirmed by model tests conducted by the Research Committee. Field tests at Iwojima, however, showed that this relationship was invalid for low values of Q. A parameter, $\xi = \frac{Q}{g^{1/2} z^{3/2}}$, was introduced to indicate the volume of air within the aerated region of the bubble jet. The experimental tests in the wave tank were carried out with a ξ between 0.41×10^{-3} and 2.04×10^{-3}. The tests at Iwojima had ξ between 0.5×10^{-4} and 2.0×10^{-4}; therefore, it appears that ξ is useful guide in determining bubble efficiency. A value of ξ of



Exp.	Tidal level m.	Air used l/m/sec.
A	0.3	13.0
B	0.4	11.7
C	2.7	11.7
D	0.3	12.0
E	2.5	

Figure 26. Horizontal current at various depths and displacements at the Iwojima breakwater.

1.8×10^{-4} was established as the limiting value below which the $U \propto Q^{1/3}$ relationship fails. (1)

The length of the pipe was not sufficient to prevent diffraction at the ends of the pipe. This increased the wave heights in the lee of the breakwater and led to inaccuracies in the wave reduction analysis. Despite this handicap the tests indicated that the breakwater was effective in substantially reducing the waves. (See Table 11). The Committee uses the term "practically annihilated" when the wave height is reduced by 1/2, and consequently, the wave energy by 3/4.

	Test D	Test F
Wind velocity	7.8 m/sec	11.5 m/sec
Air consumption	14 l/sec/m	16 l/sec/m
Power applied	1.01 KW/m	1.13 KW/m
Wave period	2-3 seconds	short and long waves
Initial mean wave height*	18 cm	43 cm
Reduced mean wave height*	13 cm	27 cm
Initial mean wave period*	2.2 sec.	2.9 sec
Reduced mean wave period*	2.1 sec	3.5 sec
Reduction ratio*	47%	63%

*one-third-highest waves
Table 11. Wave reduction at Iwojima.

On the Study of a Pneumatic Breakwater, p. 20-1.

Figures 27 and 28 are Fourier analyses of the wave spectra for the two tests. The sharp jumps in the reduced wave at low periods are probably due to the diffraction.

(1) Research Committee for Hydrology, Research Institute for Applied Mechanics, Kyushu University, Japan, On the Study of a Pneumatic Breakwater II, 1955, p. 18.

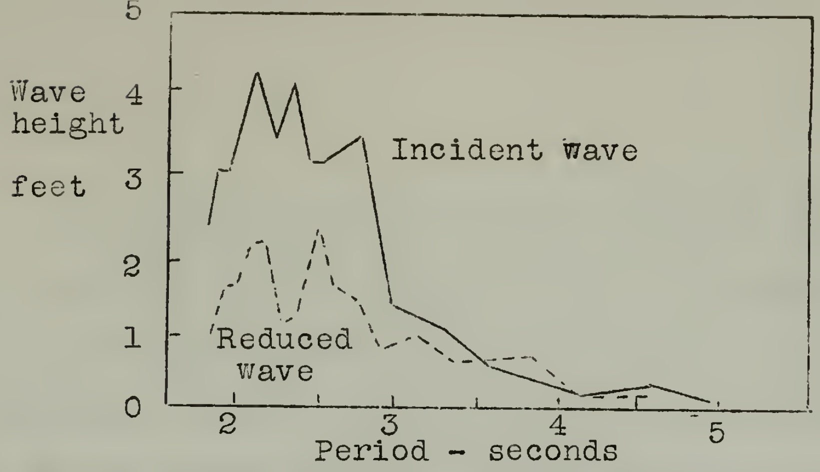


Figure 27. Fourier analysis of test D, Iwojima.

On the Study of a Pneumatic Breakwater, II, p. 20-1.

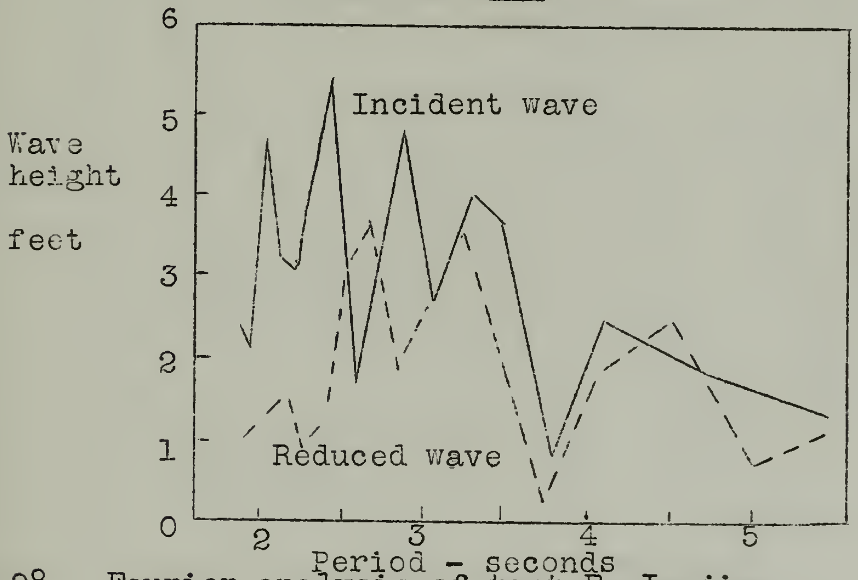


Figure 28. Fourier analysis of test F, Iwojima.

On the Study of a Pneumatic Breakwater, II, p. 20-1.

When the air pipe was designed a coefficient of vena contracta of air into water of 0.6 was assumed. Tests showed that the coefficient varied with the quantity of air emitted. For a 1.5 mm diameter hole the coefficient varied as follows: (1)

Q 1/sec/m	5	10	15	20
Coefficient of vena contracta	0.32	0.39	0.45	(0.47)

(1) Ibid. p. 24

The location for the second series of tests was chosen as Hajima Island off Nagasaki Harbor. This site was selected, as the waves were longer, and afforded an opportunity for the Committee to survey the efficiency of the breakwater under conditions more apt to be met in practice. Figure 29 is a plan of the test installation.

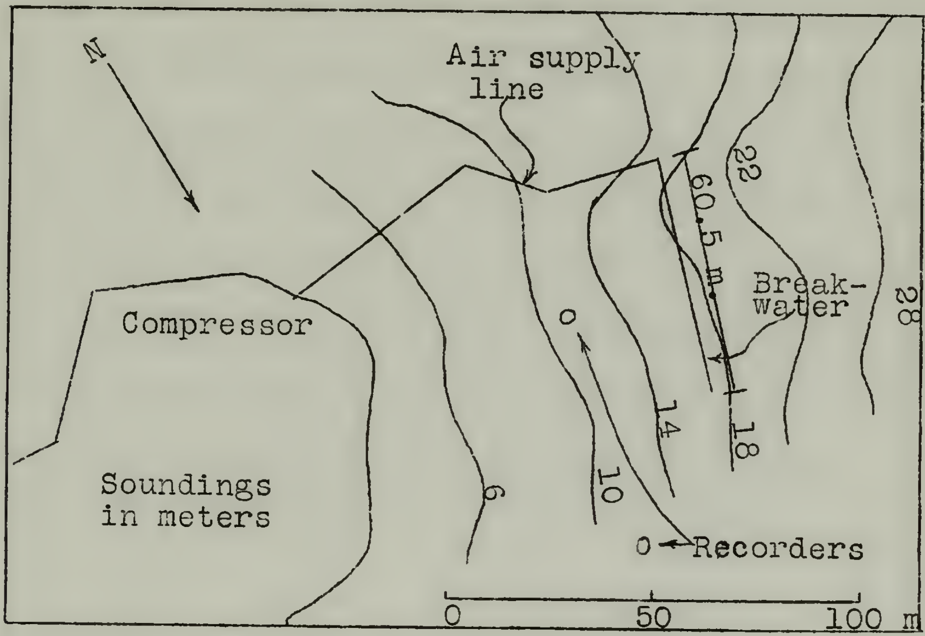
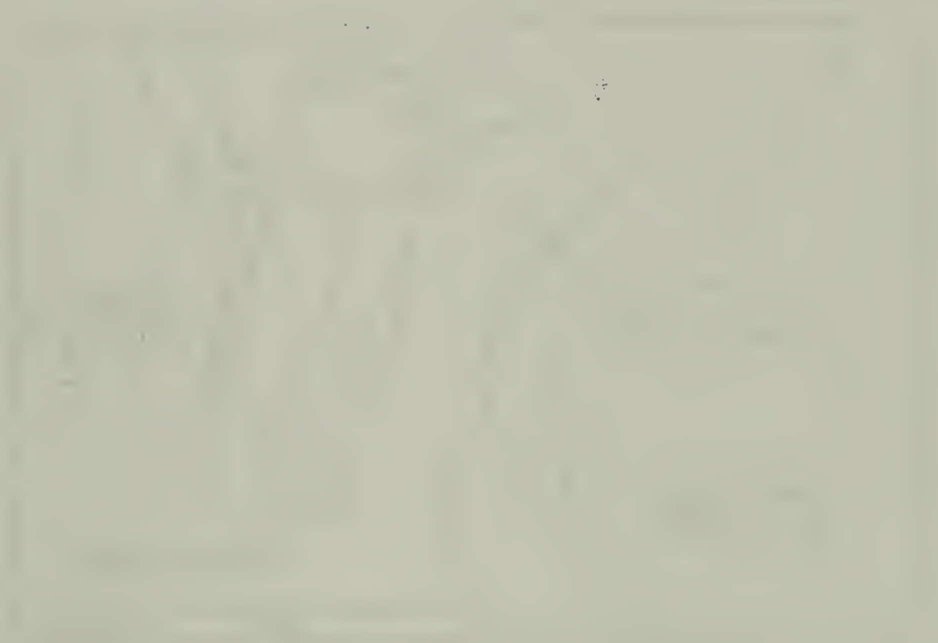


Figure 29. Plan view of experimental breakwater at Hajima.
<u>On the Study of a Pneumatic Breakwater III</u>, p. 140

The volume of air available was 150 m^3 /sec or five times that available in the first series of tests. All dimensions were double those of the first tests. The pipe was 60.5 m long, but only 5" in diameter; the depth of water was 16 m; and the design wave length was 30 m (4.37 sec. period). The pipe was not suspended during this series but was placed on concrete supports on the bottom of the harbor.



The holes in the pipe were designed with a differential head of 1/4 Kg/cm^2 at a flow of 75 m^3/min. This improved the efficiency a great deal. A coefficient of vena contracta of 0.4 was selected compared to the 0.6 assumed in the design of the first installation. 2mm diameter air holes were selected and spaced at 52.5 holes/m.

Water velocity measurements were made, as in the first series, with similar results in general. Figure 30 shows the relationship between the horizontal water velocity and the depth at various distances from the air pipe. Figure 31 shows the relationship between the horizontal velocity and the distance from the air pipe, for various depths. The graphs point out that the velocity decreases with distance from the pipe, but the current thickness increases, the product of the two increasing.

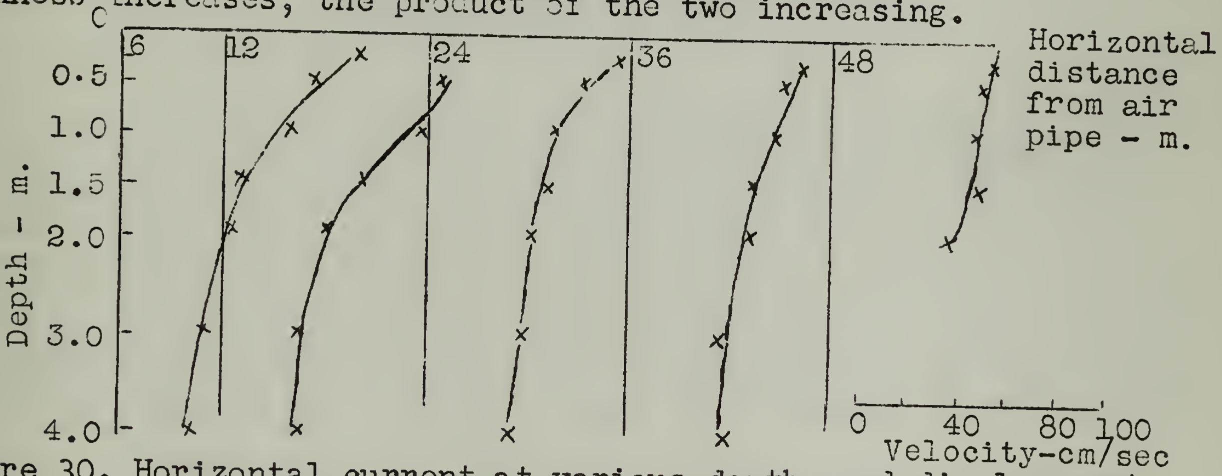
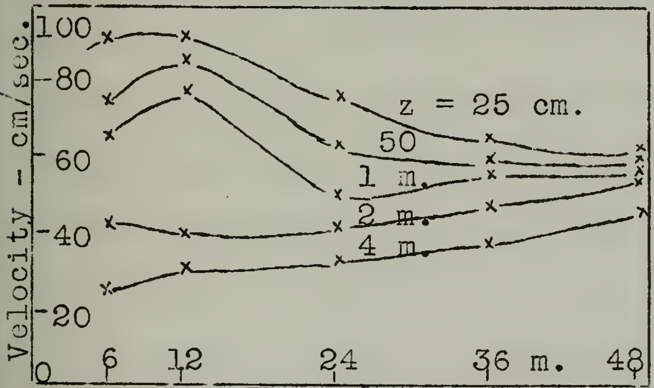


Figure 30. Horizontal current at various depths and displacement at the Hajima breakwater.

On the Study of a Pneumatic Breakwater III, p. 142

Figure 32 is a graph of horizontal water velocity, at a distance of 12 meters from the air pipe and at a depth of

50 cm, plotted against the volume of air emitted. This data varies markedly from that obtained at Iwojima. The Hajima data maintains the relationship $U = 0.314\ Q^{1/3}$ throughout the range of ξ from 0.39×10^{-4} to 1.56×10^{-4}, well below the critical ξ found in the first series of tests. Additionally, the velocity was much larger for an equal volume of air; consequently, the bubbles were much more efficient than in the previous tests.



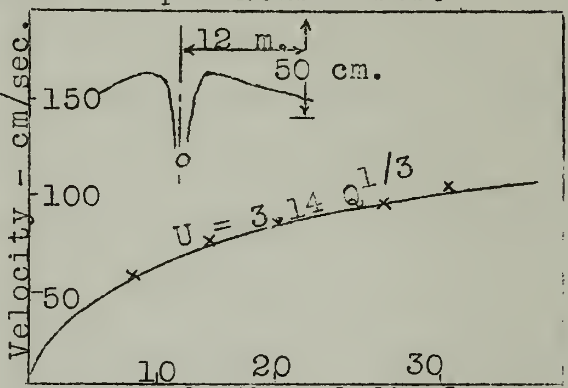


Figure 31. The relationship between current, depth and displace-
Figure 32. ment, Hajima.

On the Study of a Pneumatic Breakwater III, p. 142.

"The explanation of the increased efficiencies mentioned can be given as follows. We succeeded in reducing the pressure difference of the pipe by using a pertinent coefficient of contraction. Consequently, the diameter of each bubble became smaller (observable even with the naked eyes) and the maximum ascending velocity of the bubble was reduced. Therefore, loss of energy is presumably reduced. Secondly, due to the deeper location of the pipe, the energy of the bubble at the depth of pipe can be transferred to the upper water surface with less energy loss; consequently, the energy of the bubble is transformed more efficiently into energy of the water current. (1)

(1) Research Committee for Hydrology, Research Institute for Applied Mechanics, Kyushu University, Japan, On the Study of a Pneumatic Breakwater III, paper submitted to the Japan Society of Coastal Engineering, 1956, p. 140.

The increase in surface velocity with the increase in depth of the air pipe (tidal variation) was pointed out on page 60.

The first annihilation tests were made before the construction was completed, with only the wave recorder behind the breakwater in place; however, the wind and waves were very steady, and consequently, the characteristics of the waves taken before and after the annihilation did not vary appreciably from those during the test. The oncoming wave was inclined about 30° to the breakwater. No diffraction was noticed. The initial wave had periods less than 4.5 sec., and the major components of the wave had periods between 2.5 and 4.0 seconds. The reduced wave had a period similar to the original wave and was reduced throughout its range of periods. (See Figure 33.) The wind velocity was 7 m/sec, the depth of pipe was 16.78 m, the air consumption was 19 l/sec/m, and the power applied was 1.87 KW/m.

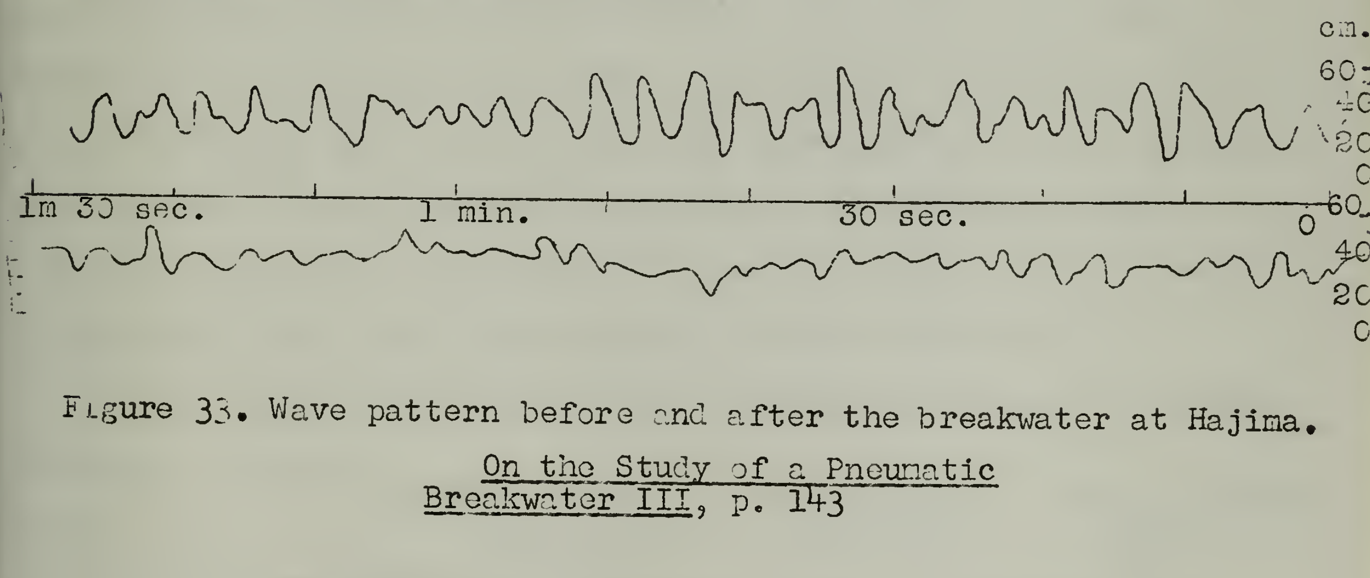


Figure 33. Wave pattern before and after the breakwater at Hajima. On the Study of a Pneumatic Breakwater III, p. 143

The Committee determined from an analytical study that the power required to annihilate a wave was = $0.002\ L^{2.5}$ KW/m,

where L is in meters; therefore, for a 4.0 sec. wave (L =25 m) the power required would be 6.25 KW/m. Evans determined that the power in the opposing current required to completely stop a similar wave (H/L = 0.01), would be 0.29 $L^{2.5}$ X 10^{-4} HP/', where L is in feet, (Table 4) or 0.00138 $L^{2.5}$ KW/m where L is in meters. For this wave the power in the water current would be 4.3 KW/m; however, to reduce the wave to 1/2 height would take only 72% (Table 6) of the power for complete reduction or 3.08 KW/m. The applied power is about seven times the power in the current or 21.6 KW/m. Assuming the compressor efficiency is 50%, the power in the air is 10.8 KW/m. The power in the compressed air in the actual test was 1.87 KW/m of pipe, or only 30% of that predicted by the Committee and approximately 17% of that estimated by Evans.

Another test, conducted when the waves were longer, showed that waves up to 5 sec. (L = 39 meters) were dampened. The test was disturbed by a strong northerly wind which tilted the direction of the waves. The longer waves were coming from a direction of 45° while the shorter ones were approaching from a direction of almost 90°. This confused the picture, and therefore, the analysis of the test ignored the shorter waves (less than 3.0 sec.) as they would have been easily dampened by the breakwater.

The highest one-third of the remaining waves had the following characteristics:

	Average height	Average period	Average length
Initial wave	96.4 cm	4.42 sec.	30.5 m
Dampened wave	66.3 cm	4.67 sec.	33.9 m

Dampening ratio = 0.69
Wind velocity 8m/sec., Air consumption 17.46 l/sec/m
Depth of pipe 16.25 m Power required 1.68 KW/m

The increase in the wave period between the original and the transmitted wave is due to the fact that a longer wave is less susceptible to dampening. The waves from 3-5 sec. were dampened almost equally in this test.

To determine the power necessary to reduce the transmitted wave to 1/2 the incident wave height, Table 6, can be used. For a wave with H/L of 0.03 the power must be multiplied by 44/26 to decrease the dampening ratio from 0.69 to 0.50. In this case, 1.68 X 44/26 = 2.84 KW/m. The Research Committee's theoretical power would be 10.3 KW/m, and Evan's 20.7; therefore, the actual power is only 28% of the Committee's and 14% of Evan's estimate.

In studying the mechanism of wave reduction the Committee undertook two cases.

1. If the horizontal current is the main factor in wave reduction the results showed that

$$\frac{P}{\rho g^{1.5} L^{2.5}} = \frac{h}{L} f_1 \left(\frac{h}{L}\right) \psi_1 \left(\frac{z}{h_o}\right)$$

where h is the thickness of the horizontal current and h_o is the atmospheric pressure.

2. If turbulent viscosity is the main factor in wave reduction then the results showed

$$\frac{P}{\rho g^{1.5} L^{2.5}} = \left(\frac{L}{z}\right)^5 \psi_2 \left(\frac{z}{h_o}\right)$$

Therefore, to achieve maximum efficiency in case 1, h/L should be small, and in case 2, L/z and ξ should be as small

as possible. These requirements are contrary to each other. Taylor and Evans believe that case 1 is more applicable, while the Committee is inclined to accept case 2. Further tests should show which is more applicable. (1).

In the reported tests the power requirements were considerably more than might be expected by the formula $P = 0.002\ L^{2.5}$ indicating that there is something wrong with the formula. The assumptions used in deriving the equation were: 100% efficiency of the bubble jet, no action of turbulent viscosity, and all of the wave annihilation due solely to the horizontal currents. The Committee examined the effect of turbulent viscosity in hopes of solving the problem.

Denoting the turbulent velocity by αU and the mixing distance by βh, where U is the horizontal velocity and h is the thickness of the current, the turbulent viscosity is $\alpha\beta Uh$. α and β may be determined by experiments. Their product, $\alpha\beta$, was found to be 0.016 in a jet stream.

All of the waves that will just be stopped by a horizontal current velocity U_1 will be given a wave number, k_1. The wave velocity = 4U, and $k_1 = 2\pi/L_1$. A parameter which will denote the efficiency of the viscosity of the breakwater is $a_1 = 4\alpha\beta k_1 h$. A wave amplitude is expressed by $e^{i(kx-\sigma t)}$. a_1 contributes to the imaginary part of k, k_i. k_i is the factor affecting dampening, $e^{-k_i x}$.

(1) Ibid, p. 145.

Figure 34 is a plot of $\left(\frac{k}{k_o}\right)$ against δ where δ is the ratio of 4U/C, C being the wave velocity. It is seen that with no viscosity ($a_1 = 0$) k/k_o is discontinuous at $\delta = 1$. With little viscosity the k/k_o ratio increases slightly from $\delta = 0.5$ onward, and hence, waves can be permanently reduced even if the horizontal current is less than C/4. This is in agreement with Evans.

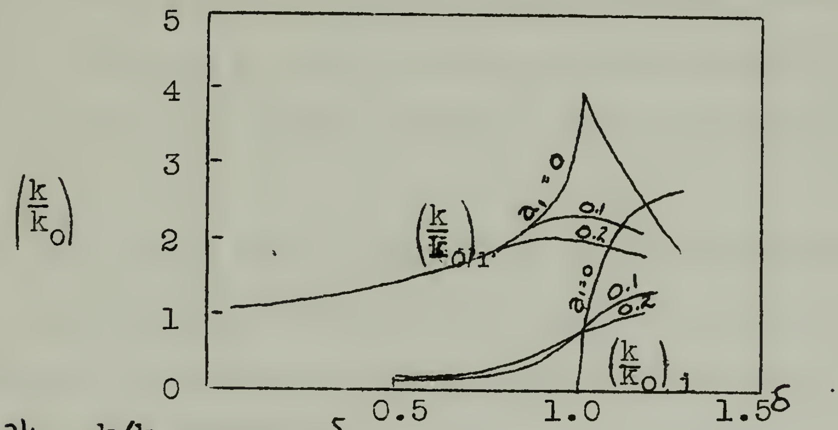


Figure 34. k/k_o versus δ

On the Study of a Pneumatic Breakwater III, p. 145

Figure 35 is a larger scale plot of $(k/k_o)_1$.

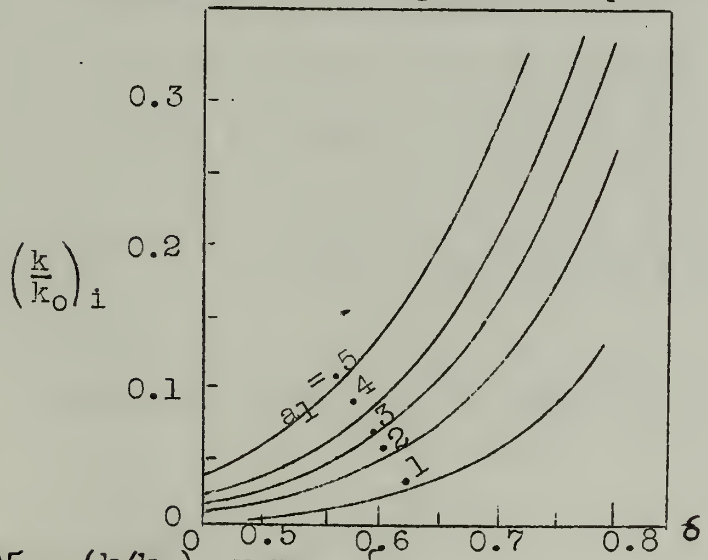


Figure 35. $(k/k_o)_i$ versus δ

On the Study of the Pneumatic Breakwater III, p. 146.

The results of the tests at Hajima indicate that this approach is correct. By using Figure 30 the current at x = 12 m is 1.0 m/sec, and the depth of the current is 7 m. It is difficult to determine the horizontal extent of the mixing distance; therefore, a trial distance of 40 m (where U is 70% of its maximum) is used. A current of 1.0 m/sec can stop a wave that has a velocity of 4.0 m/sec. A 4 m/sec wave has a length of 10.2 m and a k_1 of 0.612/m. $a_1 = 4\alpha\beta k_1 h = 0.274$. This data is constant for the test set-up and for a constant volume of air, regardless of the wave conditions.

The first test reported at Hajima annihilated waves of L = 25 m. An analysis of this wave using the new turbulent viscosity criteria should be interesting. For L = 25 m, $k_o = 0.251$/m, $C = 6.25$ m/sec. $\delta = 4.0/6.25 = 0.64$. From figure 35 $(k/k_o)_1 = 0.089$; therefore, $k_1 = 0.251 \times 0.089 = 0.0223$. The dampening coefficient is $e^{-0.0223 \times 40} = 0.411$. It can be seen from Figure 33 that the dampening ratio is close to this figure.

The second reported test had a wave of approximately 30 m length, $k_o = 0.209$, $C = 6.89$, $\delta = 4.0/6.89 = 0.58$. From Figure 35, $k_1/k_o = 0.056$, then $k_1 = 0.0117$, and the dampening factor is $e^{-0.0117 \times 40} = 0.634$. The dampening ratio is 0.60 which is within reason. (1)

During the summer of 1956, Mr. Laurie conducted "some

(1) Ibid, p. 145 - 46.

quite successful" experiments (1) at Dover (2). He is currently preparing to build a pneumatic breakwater 900' long to span two of the stone breakwaters in the harbor. The results of the experiments and the proposed breakwater will add much to the existing knowledge of pneumatic breakwaters.

In view of the full size tests conducted by the Japanese, it will prove beneficial to check the pneumatic breakwater theories, which were proposed earlier, with this recently acquired data to see which ones agree most closely with actual practice.

Taylor made his analytical study on the premise that the waves would be completely stopped; however, there is no actual data on complete wave annihilation. By computing the velocities of the horizontal currents predicted by Taylor and modifying them by Evan's reduction factor, (Table 6), for the dampening ratio actually obtained, we can evaluate the combined work of Taylor and Evans.

For the first test at Hajima L = 25 m and h = 7 m.

$$\frac{\alpha_m^2}{Z} \quad \frac{L}{2\pi h} = \frac{25}{2\pi 7} = 0.57.$$

From Figure 14 α_m = 3.7

$$U^2 = \frac{Lgh}{2\pi h \alpha_m^2} = \frac{Lg}{2\pi \alpha_m^2} = \frac{25 \times 32.2}{2\pi \times 3.28 \times 3.7^2} = 2.85$$

$$U = 1.69 \text{ m/sec.}$$

(1) The results of the experiments have not yet been published.

(2) A. H. Laurie, letter to the author, January 21, 1957.

The dampening ratio was approximately .45; therefore, from Table 6, the power requirements are .67 of that for complete reduction and $U = \sqrt[3]{.67} = .87$. Therefore, the predicted U would be 1.69 X .87 = 1.47, where 1.0 m/sec. was observed.

The second test at Hajima had an L = 30.5 m and h = 7 m The dampening ratio was .69; therefore, the P required would be 61% of that for complete stopping, and the U would be $\sqrt[3]{.69} = .88$. The predicted U would be .88 x 1.92 = 1.7 m/sec; whereas, 1.0 m/sec was observed. In each case, Taylor's work modified by Evan's power reduction factor, predicted a higher required current than was found necessary in practice. Turbulence may be the missing link.

Taylor estimated that, barring any losses, the depth of the horizontal current should be .28 times the depth of the air pipe. At Iwojima, where the air pipe was at 8 m below the surface, the depth of current should have equaled .28 x 8 = 2.24 m. It was observed to be 3 m. At Hajima the pipe was 16 m below the surface, and the depth of current should have been 4.5 m. It was found to be 7 m.

Taylor's analogy to Schmidt's work indicated that the velocity of the horizontal currents should equl 1.9 $(Qg)^{1/3}$ ft/sec with Q in ft^3/sec/ft or using Q in l/sec/m, 0.406 $(Q)^{1/3}$ m/sec. The Research Committee determined from their tests at Hajima that U = 0.314 $(Q)^{1/3}$ m/sec. However, the Hajima tests showed a higher value of U, with the same volume of air than was experienced at Iwojima; consequently, more efficient breakwaters yet will probably bring the

value of U close to Taylor's prediction.

The Franzius tests indicated that waves shallower than H/L = 0.05 were difficult to reduce. The four reported Japanese tests had H/L ratios between 0.01 and 0.03, yet all were substantially reduced.

Laurie proposed that orbital velocity may be a strong factor in the efficiency of a pneumatic breakwater. He showed from the Franzius Institute test data that there was no wave reduction when the orbital velocity was less than 1.3 ft/sec. Test D at Iwojima had an initial wave height of 18 cm and a period of 2.2 sec. The orbital velocity was therefore, $\frac{18 \pi}{2.54 \times 12 \times 2.2} = 0.84$ ft/sec., well below the proposed limiting value of 1.3 ft/sec, yet the reduction ratio was 0.47.

It is interesting to note that of the four methods proposed for determining water current velocity or the power required for wave reduction, all methods, except Evan's, are independent of the wave height.

CHAPTER V

THE USE OF THE PNEUMATIC BREAKWATER IN AMPHIBIOUS WARFARE

Wave conditions played an important role at both Iwo Jima and Normandy, as related in Chapter I. In view of the developments in pneumatic breakwater design, it is interesting to see what effect a pneumatic breakwater might have had in each case.

If a breakwater similar to but longer than the one used at Hajima had been used at Iwo Jima, the following wave reductions would have been achieved.

$k_1 = .612/m.$ $a_1 = .274$ $x = 40$ m. $U = 1.0$ m/sec
$Q = 19$ l/sec/m. $h = 7$m.

T sec.	L m.	k_o /m.	δ	k_1/k_o	k_1 /m.	k_1x	Dampening coeff; transmitted ht as % of initial height	Transmitted energy as % of initial energy
3	14	.449	.851	.70	.31	12.4	--	--
4	25	.251	.64	.090	.023	.92	39.8	15.8
5	39	.161	.51	.031	.0050	.20	82.0	67
6	56.1	.112	.43	.015	.0017	.068	93.4	87

Table 12. Theoretical wave reduction data for the Hajima breakwater.

Reduction of Energy Predicted With "Hajima" Breakwater for Various Waves.

If the breakwater were placed on the bottom, the ratio of L/D for the 5 and 6 second waves would have been 2.44 and 3.46 respectively, therefore, the waves would have been in a transitional state, and the reductions listed above would have to be modified. However, if the breakwater is suspended at a depth of 16 m in water 30 m deep, the waves remain deep-water waves, and the above reductions are valid.

To increase the wave stopping power of the breakwater, the volume of air is increased to 30.5 l/sec/m (20 cfm/ft), and the air pipe is lowered to a depth of 28 meters. This breakwater will be referred to as breakwater A.

$U = 1 \text{ m/sec} \times (30.5/19)^{1/3} = 1.17 \text{ m/sec.}$

There is no known way of accurately determining the depth of the current generated by a pneumatic breakwater in advance of actual tests; therefore, in view of the following results, which were obtained at Iwojima and Hajima, it will be assumed that $h = 12.5$ m.

$z = 8$ m	$h = 3$ m	Iwojima
$z = 16$ m	$h = 7$ m	Hajima
$z = 28$ m	$h = 12.5$ m	Breakwater A

The distance of horizontal travel of the current is more difficult to estimate. The Japanese tests gave these values of "x".

$z = 8$m	$Q = 14$ l/sec/m	$x = 13$ m	Iwojima
$z = 16$ m	$Q = 19$ l/sec/m	$x = 40$ m	Hajima

The value of x in Breakwater A is assumed to be 80 m.

$z = 28$ m $Q = 30.5$ l/sec/m $x = 80$ m

The assumed value of 80 m appears reasonable and probably is on the conservative side.

$U = 1.17$ m/sec $\qquad h = 12.5$ m. $\qquad x = 80$ m.

$C = 4\ U = 4.68$ m/sec

$T = 4.68 \times 3.28\ /5.12 = 3$ sec

$L_1 = 5.12 \times 3^2\ /3.28 = 14.05$ m.

$k_1 = 2\pi/14.05 = .447/\text{m}.$

$a_1 = 4 \times 0.016 \times .447 \times 12.5 = .357$

T sec.	L m.	k_o /m.	δ	k_i/k_o	k_i /m.	$k_i x$	Dampening coeff; transmitted Ht as % of initial height	Transmitted energy as % of initial energy
4	25	.251	.75	.27	.068	5.4	45	--
5	39	.161	.60	.085	.0137	1.1	33	11
6	56.1	.112	.50	.035	.0039	.31	73	53
7	76.4	.0822	.43	.015	.0012	.099	90	81

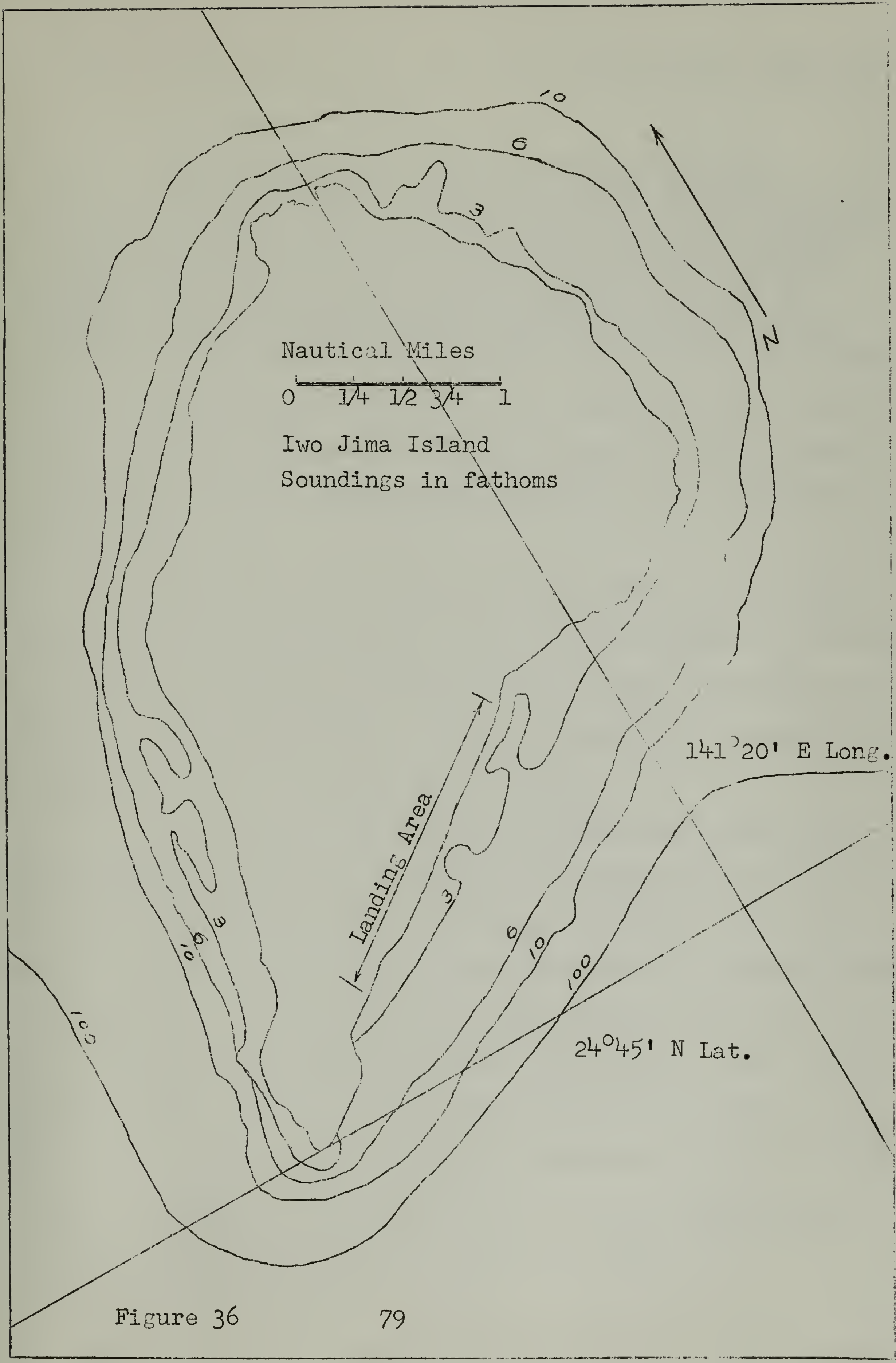
Table 13. Theoretical wave reduction data for breakwater "A".

Reduction of Energy Predicted with
Breakwater "A" for Various Waves

The breakwater would have to be placed in water at least 39 m deep if the 7 second wave is to be a deep water wave, otherwise, the wave reduction predicted for this wave would have to be modified.

Figure 36 is a chart of the immediate Iwo Jima area. The original landing beaches are on the southeastern side of the island.

Table 14 lists the computed characteristics of the



Nautical Miles
0 1/4 1/2 3/4 1
Iwo Jima Island
Soundings in fathoms
N
10
6
3
Landing Area
141°20' E Long.
24°45' N Lat.
100

Figure 36

waves on the southeastern beaches for D-Day, February 19, 1945, and for a short time before and after.

> "In computing wave characteristics, we used chiefly winds as indicated by isobar orientation and spacing, since actual wind observations were either sparse or lacking. No attempt was made to derive surf conditions from the computed deep-water waves, nor was the contribution of swell considered. Both of these factors would be expected to produce breaker heights somewhat greater than the wave heights listed in the enclosed table, particularly on the southeast beaches with seas from the east through south." (1)

The energies contained in the incident waves at Iwo Jima are also listed in Table 14 along with the residual energies that would have resulted if the Hajima breakwater and breakwater A had been used.

Table 15 gives the swell conditions in the vicinity of Iwo Jima during the same period. Some of the periods of the swell were not readily available. They have been assumed by taking the average of the flanking periods. The wave energy in each swell has been computed and is listed also in Table 15.

At Iwo Jima, "The Weather deteriorated toward mid-afternoon of the first day, and thereafter was most erratic". (2) The wave and swell data from noon on D-Day until 2400 on D + 6, therefore, will be evaluated in conjunction with the expected results from breakwater A. The average wave energy during this period was 32,400 ft-lb/ft of wave crest per wave. Only 15.4% of this energy, or 4,990 ft-lb/ft, would be transmitted past the breakwater. The average energy of the swell during this period was 28,100 ft-lb/ft

(1) John Lyman, Director Division of Oceanography, Hydrographic Office, letter to the author, March 19, 1957.

(2) Isely and Crowl, p. 517.

COMPUTED WAVE CHARACTERISTICS, IWO JIMA 18 - 26 February 1945
(Southeast Beaches)

Date	Local St'd Time	Observed Wind direction	Wind Force Beaufort	Computed wind direction	Wind Force Beaufort	Computed Wave conditions Height Feet	Period Second	Length Feet	Initial Energy Ft-#(1)	Residual Energy Hajima(1)	Residual Energy "A"(1)
1	2	3	4	5	6	7	8	9	10	11	12
18	1630	NNE	3			2	4	82	2,620	415	
	2230			N	2	2	2	20	640	---	---
19	0430			NNE	3	2	3	46	1,470	---	---
	1030			NE	1		negligible		---	---	---
	2230			NE	3	2	4	82	2,620	415	---
20	0430			NE	5	6	4	82	23,600	3,730	---
	2230	NW	3			2	4	82	2,620	415	---
21	0430			NE	4	4	4	82	10,500	1,660	---
	1030			N	4	4	4	82	10,500	1,660	---
	1630			NE	4	4	5	128	16,400	11,000	1,800
	2230	NE	5			6	4	82	23,600	3,730	---
22	0430			NW	5	6	5	128	36,800	24,700	4,050
	2230	NNW	4			4	5	128	16,400	11,000	1,800
23	0430	NW	7			10	5	128	102,000	68,200	11,210
	1030			NE	5	6	5	128	36,800	24,700	4,050
	1630			NE	5	7	5	128	50,200	33,600	5,520
	2230			N	5	8	6	184	94,200	82,000	50,100
24	0430	NE	4			4	5	128	16,400	11,000	1,800
	1030			E	4	4	4	82	10,500	1,660	---
25	0430			SE	5	6	5	128	36,800	24,700	4,050
	1030	SW	6			8	4	82	42,000	6,640	---
	2230			S	5	7	5	128	50,200	33,600	5,520
26	0430	S	4			4	5	128	16,400	11,000	1,800
	1030			SW	4	4	4	82	10,500	1,660	---

Table 14
From letter by John Lyman, U. S. Navy Hydrographic Office to the author.

(1) Columns 10 - 12 computed by author.

Swell in the vicinity of Iwo Jima February 1945
Extracted from COMPHIBPAC Aerological Reports

Date	Time LST	Lat. N	Long. E	Direction	Height Feet	Period Sec.	Energy ft-#(1)
1	2	3	4	5	6	7	8
17	04	16	144	E	3	10	36,800
	10	17	143	NE	2	9	13,300
	16	18	142	NE	3	9	29,800
	22	18	142	NE	3	9	29,800
18	03	20	142	NE	4	9	52,900
	09	21	142	NE	5	9	82,600
	15	22	142	NE	5	9	82,600
	21	23	142	NE	5	10	102,000
19	03	24	142	N	4	10	65,600
	09	25	141	N	4	15	147,500
	15	25	141	N	3	12	53,100
	21	25	141	N	3	12	53,100
20	03	25	141	N	3	10*	36,800
	09	25	141	N	3	10*	36,800
	15	25	141	N	1	10*	4,080
	21	25	141	NE	1	10*	4,080
21	03	25	141	N	3	10*	36,800
	09	25	141	N	3	10*	36,800
	15	25	141	N	1	10*	4,080
	21	25	141	NE	3	10*	36,800
22	03	25	141	E	4	10*	65,600
	09	25	141	-	1	10*	4,080
	15	25	141	E	1	10*	4,080
	21	25	141	N	3	10*	36,800
23	03	25	141	N	3	10*	36,800
	09	25	141	N	4	10*	65,600
	15	25	141	N	4	10*	65,600
	21	25	141	N	4	10*	65,600
24	03	25	141	N	4	10*	65,600
	09	25	141	N	1	8	2,620
	15	25	141	N	1	8*	2,620
	21	25	141	N	1	8*	2,620
25	03	25	141	NW	1	8	2,620
	09	25	141	N	1	8	2,620
	15	25	141	N	1	9	3,300
	21	25	141	SE	1	7	2,000
26	03	25	141	N	1	8*	2,620
	09	25	141	SW	1	8	2,620
	15	25	141	-	9#		
	21	25	141	NE	1	7*	2,000
27	03	25	141	N	1	7	2,000
	09	25	141	NE	3	8	23,500
	15	25	141	NE	3	8	23,500
	21	25	141	NE	3	8	23,500

Table 15

Boyd E. Olson, U.S. Navy Hydrographic Office letter to author, dated 10 April, 1957

(1) Col. 8 computed by author. *values assumed by author
Appears to be in error and is disregarded.

of crest per swell; therefore, on a one wave to one swell basis almost half of the energy in the combination would be eliminated. Moreover, the frequency of the swell would be approximately one-half that of the wave, and therefore, the breakwater would annihilate approximately 60% of the total energy approaching the beach. Although the swells would not be reduced, their effect on landing craft would be less than the effect of waves with the same energy, because their wave height would be lower, and they would allow more time for the craft to recover between waves.

The design wave at Normandy was 8 ft high and 120 ft long. Breakwater A would reduce this design wave accordingly:

T sec.	L m.	k_o	δ	k_i/k_o	k_i /m.	$k_i x$	Dampening coeff; transmitted Ht as % of initial height	Transmitted energy as% of initial energy
4.86	36.6	.1715	.617	.095	.0162	1.30	27	7.2

Therefore, the design wave with an energy of 61,400 ft-lb/ft would transmit only 7.2% of this energy or 4,400 ft-lb/ft. Returning to Figure 1, it is noted that by reducing the wave height by 73%, the tonnage unloaded is increased greatly.

Installations of the pneumatic breakwater to date have been made without the urgency required in an amphibious operation. To give the maximum protection the breakwater should be in place and operating within hours after H-hour. This necessitates the pre-packaging of the components of the breakwater. An expeditious means of installing and operating the breakwater would be to package all

the components for a length of the breakwater in a landing craft, such as an LCM. The packages would be interchangeable, and if one unit were lost a replacement could be substituted for it.

All previous installations have been made using metal pipe as the air pipe. The pipe has proven satisfactory, but it takes a long time to lay it. Additionally, there is the inherent trouble of leaking joints which are hard to correct once the pipe is in place. The use of a hose in place of a pipe would eliminate these two objections. The hose could be coiled on a reel carried aboard an LCM and quickly unreeled and laid, as the LCM proceeded at low speed along the line of the breakwater. A hose with a neoprene tube or liner 0.090" thick with 3 plies of nylon fabric reinforcement and with a neoprene cover 0.050" thick, would have a bursting strength of 230 psi in the 6" size, yet would be flexible enough to be reeled. The hose would weigh about 2-1/4 pounds per foot in this size and would be resistant to age, weathering, and salt water.

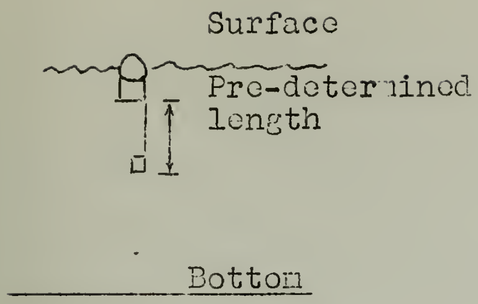
Mr. F. J. Pechal, Development Engineer of the Raybestos-Manhattan Incorporated, attempted to spin 1/8" holes in a sample of the above hose. This was not successful as the holes varied in size and were tapered. Drilling tears the rubber and makes jagged edges. Further work on the drilling of small holes in similar hoses is needed. In the meantime, small even holes could be made in the hose by inserting metal grommets.

When the system is in operation, the 6" hose would have a buoyancy of $\frac{3.14^{2}}{144}\pi \; 64 = 13.7 = 2.25 = 11.45$ lb/ft net

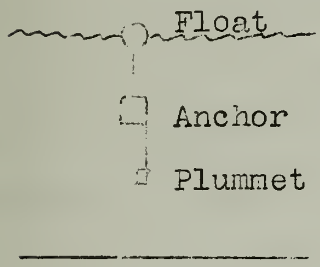
buoyancy. Therefore, anchors would have to be used to overcome this buoyancy. As the hose is laid out, there would be a heavy strain on the hose due to the anchors fastened to it. To take this strain a wire rope should be fastened to the hose, and all of the strain of setting the breakwater should be taken by this rope.

If the breakwater is to rest on the bottom, anchors would have to be clamped to the wire rope, as the hose and rope are unreeled. If the breakwater is to be suspended at an elevation, special provisions must be made. If the bottom is even, a predetermined length of anchor line would hold the hose from rising out of position. On uneven bottoms, or where the depth of water is not certain, an anchor, similar to but smaller than the anchors used on surface-laid mines, could be used to hold the hose at the right depth. (See Figure 37). When the breakwater is not in use, the air pressure in the hose would decrease, and the hydrostatic head would collapse the hose. The buoyancy due to the air would be lost, and the hose would sink to the bottom. Where the depth of water is so great that the compressors could not overcome the hydrostatic head at that depth, it would be necessary to attach floats to the hose to insure that it would not sink below its design depth.

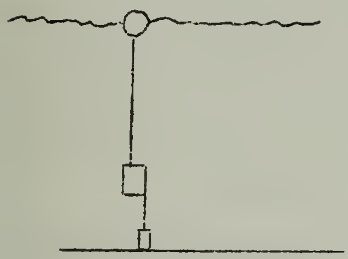
The compressors need to have a high volumetric capacity at about 50 psi gage. A gas turbine air compressor has the advantages of large volume (up to 1800 cfm), low weight (550#), and small size (57" long). However, it has the disadvantages of low efficiency and a current maximum discharge pressure of 40 psig. A compressor with a capacity of 2400 cfm at 60 psig is under development.



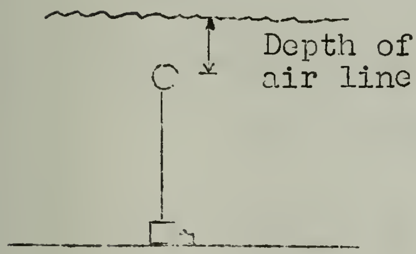
The anchor assembly consists of a float, the anchor, and a plummet. When the assembly is first laid the float and anchor are fastened together and their net buoyancy is positive. The plummet falls until the wire holding it to the anchor reaches a pre-determined length equal to the desired depth of the breakwater.



The anchor is freed from the float and partially fills with water, decreasing its buoyancy, and it sinks. The anchor wire to the float runs free from a reel inside the anchor.



When the plummet reaches the bottom the tension in the plummet wire is eliminated; this causes a pawl in the anchor to engage a rachet on the anchor wire reel. The reel stops unwinding and the anchor wire length is set.



The float is then pulled down by the anchor until the anchor is on the bottom. The air line is then at the desired depth below the water.

Figure 37. The operation of an anchor to position the breakwater at the desired depth.

For depth up to 75 ft., the gas turbine air compressor would be very good. The installation at the train ferry dock in Dover used one, and the tests at Hajima and Iwojima could have done so. For breakwater A, the depth of water of 92 ft would be too deep for the gas turbine air compressors now available.

Rotary, vane type, single stage compressors of 50 psig and 1600 cfm are available and could be used for the air supply. Two stage rotary compressors can furnish larger pressures of air if required. Rotary compressors are of such size that four of them furnishing a total of 6400 cfm could be installed in one LCM. The LCM would have to be modified in order to support the compressors; to increase the capacity of the fuel tanks; and to provide the rigging gear for handling the air hose, wire rope, anchors and floats. With 6400 cfm/LCM, each craft could install and supply approximately 320' of breakwater A.

For this breakwater the hose diagram would be an inverted T, the vertical hose supplying air to the horizontal ones. The length of the horizontal hose would be 320 ft., and the length of the vertical one would be the depth of the breakwater plus 100 ft., for freedom of the LCM at its mooring, or a total of 192 ft.

The friction loss in a 6 in. stem would be:

$$D = \frac{.7\,Q^{1.85}\,l}{d^5\,p\,1000} = \frac{.7 \times 6400^{1.85} \times 192}{6^5 \times 48 \times 1000} = 3.95 \text{ psi}$$

The loss in the 6 in. horizontal legs would be:

$$D = \frac{.7}{6^5 \times 46 \times 1000} \int Q^{1.85}\, dl \qquad Q = 20\, l$$

$$D = 1.96 \times 10^{-9} \int_0^{160} (20\, l)^{1.85} dl$$

$$D = 4.98 \times 10^{-7} \left[\frac{l^{2.85}}{2.85}\right]_0^{160}$$

$D = .327$ psi.

The orifice loss is about 4 psi-Hajima design data.

The total loss in head at the extreme orifices would be $\cong$ 8.3 psi; therefore, approximately 41 psi would be available to overcome the hydrostatic head, and the breakwater could be used at any depth up to 92 ft.

The neoprene hose has a temperature limitation of 250°F. The discharge temperature of the compressors varies from 300°F to 425°F. Consequently, the compressed air would have to be cooled before reaching the neoprene hose. This could be accomplished by using aftercoolers with the compressors, or by supplying the air to the hose through a heat exchanger bank suspended in the water.

The sequence in installing and operating the breakwater would be:

1. A control boat would lay out floats, indicating the location of the breakwater and showing each LCM's section of it.

2. Each LCM would start at one end of its segment and lower a heavy anchor fastened to the end of the wire rope and hose.

3. A slight strain would be kept on the end anchor to keep the rope and hose stretched out as they are being laid.

4. Intermediate 150 lb anchors would be attached to the rope every 10 ft.

5. A float would be attached to the free end of the vertical hose, as the free end is unreeled, and then they would be thrown overboard.

6. The wire rope would be made longer than the hose so that the hose could be stretched out its full length on the bottom. After the hose is stretched out the end of the rope would be thrown overboard. (See Figure 38.)

7. The LCM would return to the area of the center of the hose and moor with one anchor on either side of the breakwater. The moor would keep the craft from swinging with too large a radius around its anchorage and would reduce the length of the vertical hose required.

8. The LCM would connect the floating end of the vertical hose to the compressors, and would commence supplying air to the breakwater.

9. The pressure would be adjusted to the minimum necessary to obtain air bubbles all along the hose. As the tide changes, the pressure would have to be adjusted to the current depth of the breakwater.

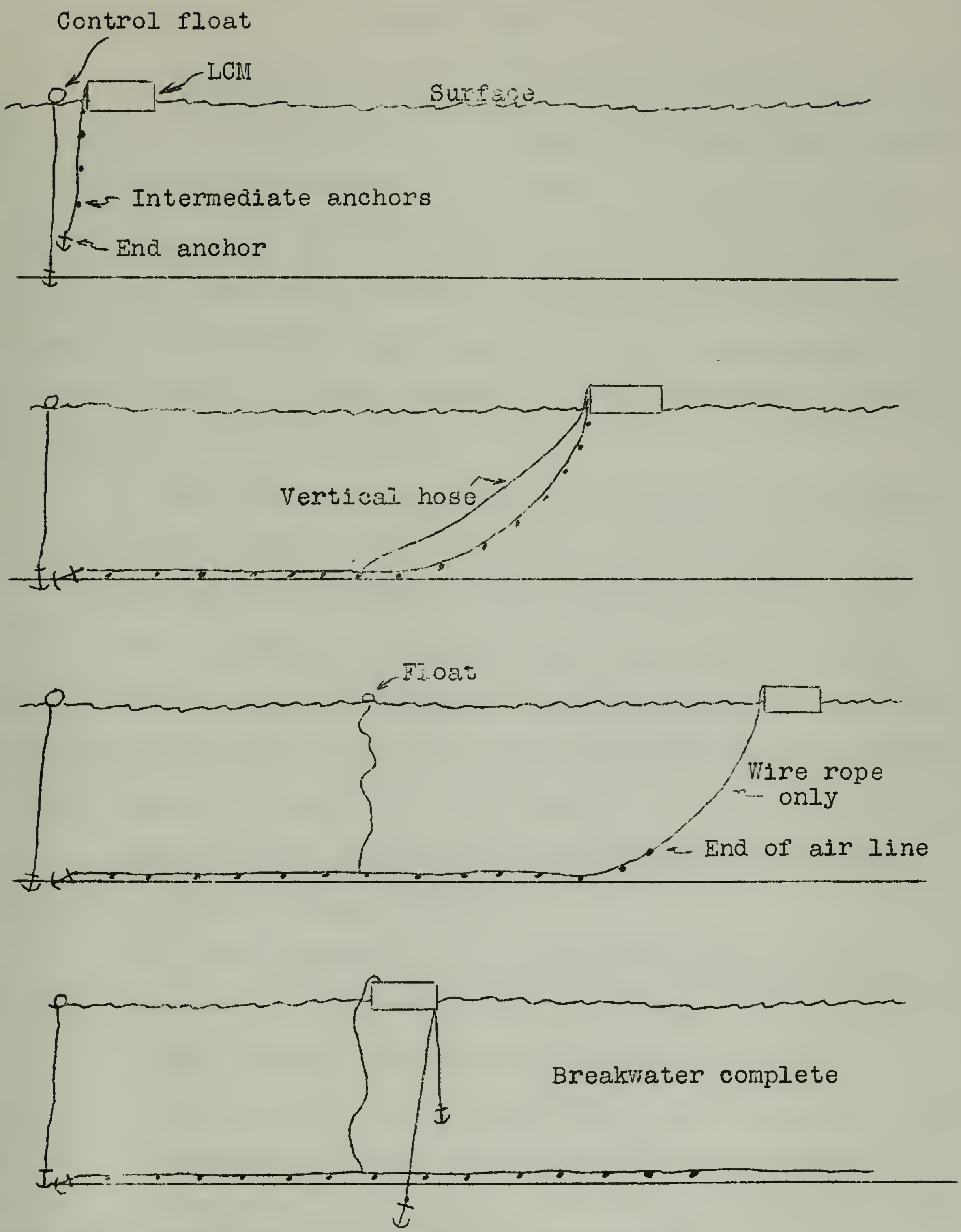


Figure 38. The laying of a Pneumatic Breakwater.

CHAPTER VI

CONCLUSIONS

1. Despite the thought and effort that have been applied to the study of the wave reducing mechanism of the pneumatic breakwater, a great deal more remains to be done. The experiments at Iwojima and Hajima are the first full size ones that have been recorded sufficiently to be of use in checking the proposed theories. The Japanese turbulent viscosity approach appears to be verified by these tests; however, two installations are not considered sufficient for a complete stamp of approval.

2. Even without a complete understanding of the working of the breakwater, several facts appear to be substantiated.

(a) Waves can be reduced by a pneumatic breakwater.

(b) The reduction of waves decreases rapidly as the waves pass from a deep water stage to a transitional stage and then to a shallow water stage; therefore, the breakwater should be placed at a depth equal to one-half the wave length.

(c) The power required for wave reduction increases rapidly with increases in wave length.

(d) The breakwater is most efficient when reducing a high, short wave and is least efficient in reducing a shallow wave.

3. The Japanese viscosity theory indicates that a volume of air of 20 cfm/ft can eliminate 89% of the energy in a 128' wave, 47% of the energy in a 185' wave, and 19% of the energy in a 250' wave. With an increased quantity of air these reductions could be increased.

4. The breakwater cannot yet be classified as an economical, permanent substitute for a conventional breakwater except in a location that is seldom threatened by waves and then only by comparatively short ones.

5. The pneumatic breakwater has a good future in providing temporary protection where the water is deep enough and the waves are short enough.

6. The use of wave protection during amphibious operations would contribute greatly to the reduction in casualties and the loss of landing craft and equipment.

7. A pneumatic breakwater could be transported with comparative ease to a landing area, installed and put into operation.

8. A pneumatic breakwater could furnish a high degree of protection against all waves less than 200' long.

9. A major disadvantage of the pneumatic breakwater, as compared to a "Phoenix" breakwater, is the complete absence of protection from waves appreciably longer than the design wave; therefore, this breakwater must be used where there are no high long waves, or where the calculated risk of encountering these waves can be taken.

CHAPTER VII

RECOMMENDATION

It is recommended that the U. S. Navy, in the absence of any more promising mobile breakwater, further develop the pneumatic breakwater and include it in amphibious warfare doctrine.

Bibliography

1. Bartley, Whitman, S., Lt. Col. USMC, Iwo Jima, Amphibious Epic, U. S. Marine Corps Headquarters, Washington, 1954.

2. Bates, C. C., "Utilization of Wave Forecasting in the Invasion of Normandy, Burma, and Japan", Annals of the New York Academy of Sciences, May 1949, Vol. 51, Art. 3, p. 545.

3. Beach Erosion Board, U. S. Corps of Engineers, Shore Protection Planning and Design, Techical Report No. 4, Washington, 1954.

4. Bigelow, Henry B., and Edmondson, W. T., Wind Waves at Sea, Breakers and Surf, Hydrographic Office Publication No. 602, Washington, 1927.

5. "The Brasher Air Breakwater", Compressed Air Magazine, March, 1915, Vol. XX, p. 7523.

6. Carr, John H., Mobile Breakwater Studies, Report No. N-64.2, Hydrodynamics Laboratories, California Institute of Technology, Pasadena, 1950.

7. "Discussion on Mulberry Components", The Civil Engineer in War, Institute of Civil Engineers, London, 1948, Vol. 2, p. 313.

8. Evans, J. T., "Pneumatic and Similar Breakwaters", Proceedings of the Royal Society, London, 1955 Vol. 231A, p. 457.

9. Evans, J. T., "Pneumatic and Similar Breakwaters", Dock and Harbour Authority, December 1955, Vol. 36, p. 251.

10. Haugh, Frank O., The Island War, J. B. Lippincott Company, Philadelphia, 1947.

11. Hensen, Walter, "Model Tests with Pneumatic Breakwaters", Dock and Harbour Authority, June 1955, Vol. 36, p. 57.

12. Hodge, W. J., "The Mulberry Invasion Harbours, Their Design, Preparation and Installation", The Structural Engineer, March 1946, p. 125.

13. Isely, Jeter A. and Crowl, Philip A., The U. S. Marines and Amphibious War, Princeton University Press, Princeton, 1951.

14. Jellet, John Holmes, "The Lay-out, Assembly, and Behavior of the Breakwater at Arromanches Harbour (Mulberry B)", The Civil Engineer in War, Institute of Civil Engineers, London, 1948, Vol. 2, p. 291.

15. Laurie, A. H., "The German Experiments on Pneumatic Breakwaters", Dock and Harbour Authority, June, 1955, Vol. 36, p. 61.

16. Laurie, A. H., "Pneumatic Breakwaters", Dock and Harbour Authority, May 1952, Vol. 33, p. 11.

17. Lochner, Robert; Faber, Oscar; and Penney, William; "Bombardon Floating Breakwater", The Civil Engineer in War, Institute of Civil Engineers, London, 1948, Vol. 2, p. 256.

18. Minikin, R. R., Winds, Wave and Maritime Structures, Charles Griffin and Company, Ltd., 1950.

19. Morison, Samuel Eliot, Coral Sea, Midway, Submarine Action, Little Brown and Company, Boston, 1949.

20. "The Pneumatic Breakwater at Dover", Dock and Harbour Authority, December, 1952, Vol. 33, p. 249.

21. Research Committee for Hydrology, Research Institute for Applied Mechanics, Kyushu University, On the Study of a Pneumatic Breakwater II, Japan, 1955.

22. Research Committee for Hydrology, Research Institute for Applied Mechanics, Kyushu University, On the Study of a Pneumatic Breakwater III, Japan, 1956.

23. Schiff, L. I., Air Bubble Breakwater, Report No. N-64.1, Hydrodynamics Laboratories, California Institute of Technology, Pasadena, 1950.

24. Skerrett, Robert G., "Smashing Angry Seas With Bubbles of Compressed Air", Compressed Air Magazine, January 1921, Vol. XXVI, p. 9921.

25. "The Strange Case of the Pneumatic Breakwater", Compressed Air Magazine, August 1954, Vol. 59, p. 221.

26. Sverdrup, H. U. and Munk, W. H., Wind, Sea, and Swell: Theory of Relations for Forecasting, U. S. Navy Hydrographic Office Publication No. 601, Washington, 1947.

27. Taylor, G. I., "Action of Surface Current Used as a Breakwater", Proceedings of the Royal Society, London, 1955, Vol. 231A, p. 466.

28. Todd, F. H., "Model Experiments on Different Designs of Breakwaters", The Civil Engineer in War, Institute of Civil Engineers, London, 1948, Vol. 2, p. 243.

29. U. S. Marine Corps, Terrain, Hydrography, and Weather, Landing Force Manual-2, Washington, 1955.

30. U. S. Marine Corps, Ship to Shore Movement, Landing Force Manual-4, Washington, 1956.

31. U. S. Marine Corps, Logistical Support (Including Personnel), Landing Force Manual-20, Washington, 1952.

32. Unna, P.J.H., "Waves and Tidal Streams", Nature, February 21, 1942, Vol. 149, p. 219.

33. Vagt, Alfred, Landing Operations, Military Service Publishing Company, Harrisburg, 1952.

34. Wood, Cyril Raymond James, "Phoenix", The Civil Engineer in War, Institute of Civil Engineers, London, 1948, Vol. 2, p. 336.